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Performance Criteria for Concrete Repair Materials, Phase II Field Studies

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HY	Hydraulics	OM	Operations Management
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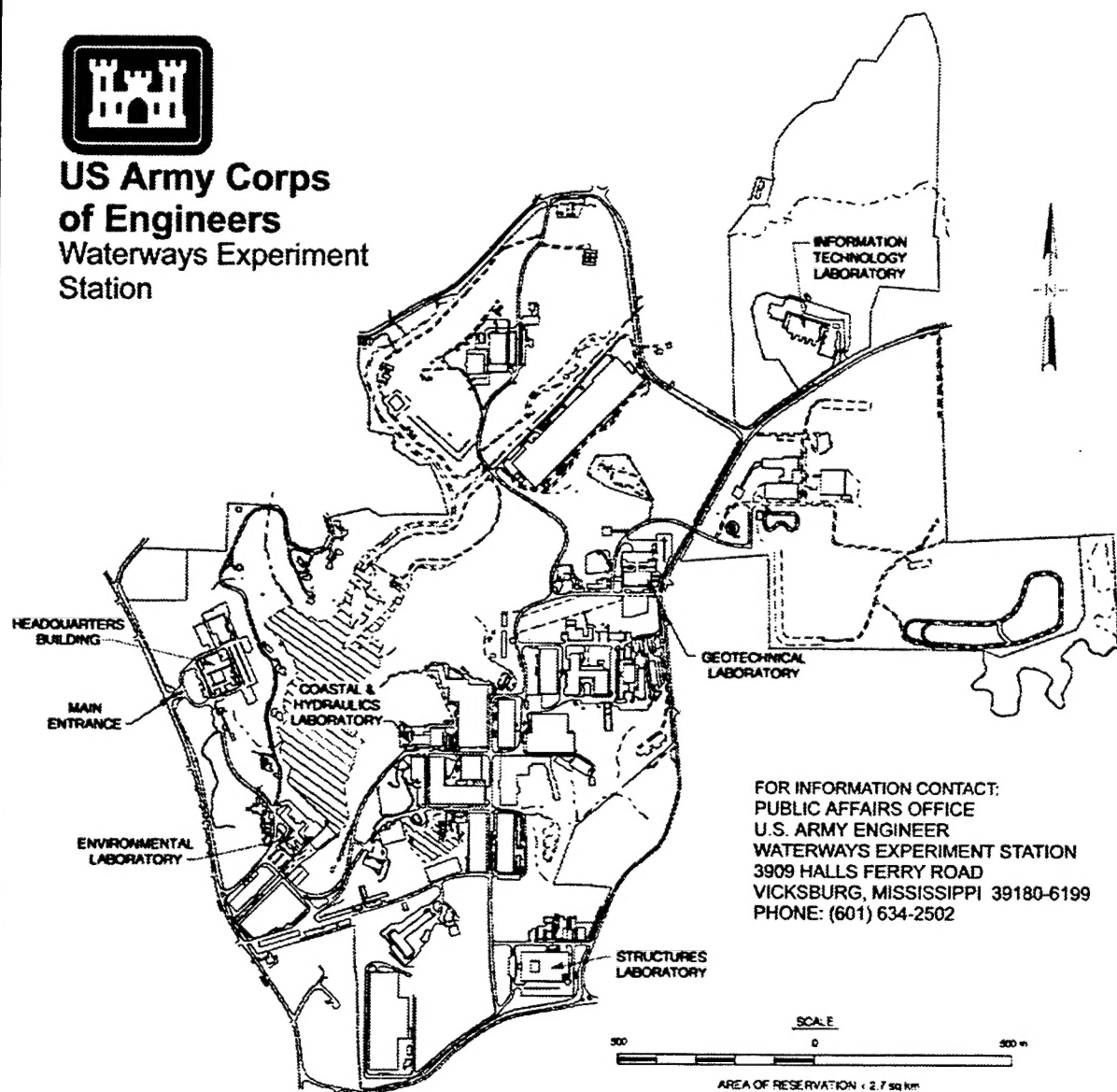
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Preface

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Unit 32637, "Evaluation of Existing Repair Materials and Methods," for which Mr. James E. McDonald, Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

The REMR Technical Monitor is Mr. M. K. Lee, HQUSACE. Dr. Tony C. Liu (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee. Mr. William F. McCleese, WES, is the REMR Program Manager. Mr. McDonald is the Problem Area Leader for Concrete and Steel Structures.

The study was performed by Structural Preservation Systems, Inc. (SPS), Baltimore, MD, under contract to WES. The study was under the direct supervision of Mr. McDonald and general supervision of Dr. Paul F. Mlakar, Chief, Concrete and Materials Division, and Mr. Bryant Mather, Director, SL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

The authors would like to acknowledge the assistance of Messrs. Garry Stevens of Bureau of Reclamation, Arizona Projects office; Mr. Thomas Kline, SPS, Chicago office; Mr. Marc Yeager, SPS, Baltimore office; and Ms. Margo Gray, SPS Corporate office, in the conduct of the study and completion of the report.

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1 Introduction

Background

Concrete repair is a complex process, presenting unique challenges that differ from those associated with new concrete construction. The concrete repair process must successfully integrate new materials with old materials, forming a composite system capable of enduring exposure to service loads, environment, and time. The durability of a concrete repair depends, to a large degree, on the correct choice and application of repair materials. Restrained volume changes of repair materials, the restraint being provided through bond to the existing concrete substrate, is a major cause of cracking and premature deterioration of concrete repairs.

Selection of appropriate repair materials requires an understanding of material properties and behavior under anticipated service exposure conditions. One of the greatest challenges to successful performance of repair materials is their dimensional behavior relative to the substrate. Relative dimensional changes cause internal stresses within the repair material, at the bond line, and in the substrate, which may result in cracking, loss of load-carrying capacity, delamination, and deterioration. Particular attention is required to select materials with proper dimensional behavior to minimize these stresses. Identification of materials that behave similarly to the substrate when subjected to loads, temperature, and moisture changes is practically impossible. The requirement for durable repairs, therefore, is that selected materials must have properties dimensionally compatible with the concrete substrate.

Thousands of materials with widely varying properties are currently being marketed for repair of concrete. Therefore, a much more sophisticated approach to addressing, controlling, and specifying durability of repairs is needed. Specifically, a more direct means is needed to link the material properties with the quality and performance of what is produced.

There is considerable pressure to develop and use performance criteria for the selection of repair materials. Development and adherence to sound performance criteria are logical ways to improve the durability of repaired structures. The introduction of such performance criteria will require improved knowledge of the relationships between composition, laboratory test results, and field performance of cement-based composites. Properties affecting dimensional compatibility between repair and existing structures are

the cornerstone of such criteria.

Structural Preservation Systems, Inc. (SPS), of Baltimore, MD, was awarded a contract by the U.S. Army Engineer Waterways Experiment Station (WES) to develop performance criteria for the selection of dimensionally compatible repair materials. Preliminary performance criteria were developed in Phase I of the overall study, and a comprehensive experimental field- and laboratory-testing program was proposed to verify these criteria (Emmons and Vaysburd 1995). The experimental program implemented in this study was an integral part of the overall effort (Figure 1) to develop performance criteria for the selection of repair materials. The interaction of the two parts of the experimental program (laboratory and field tests) with the overall research project is outlined in Figure 2.

The performance of selected, commercially available concrete repair materials was evaluated in the laboratory investigation. Each of the 12 candidate materials was subjected to a series of standard and nonstandard laboratory tests to determine material properties that were perceived to be of interest in a repair context and to provide some basic information about their behavior. A concurrent field-exposure study was initiated in which the same materials were installed in simulated repairs and exposed to differing environmental conditions. This experimental field program was conducted to enhance an understanding of the repair material behavior, especially as related to the restrained volume changes and resulting cracking sensitivity, a critical factor affecting durability of concrete repairs.

Results of the laboratory tests were recently reported by Poston et al. (1998). These tests included (a) unrestrained and restrained drying shrinkage, (b) modulus of elasticity, (c) tensile and compressive creep, (d) coefficient of thermal expansion, and (e) flexural, compressive, and direct tensile strengths. Results of field-exposure tests to evaluate the durability of these materials are reported herein. Results of the laboratory and field tests will be correlated (Phase III) to form a basis for development of performance criteria for cement-based materials that will provide durable concrete repairs.

Objective and Scope

The principal objective of the field-testing program was to validate preliminary performance criteria under realistic conditions, i.e., actual repair geometry, mixing, placing, consolidation, curing, and varying weather conditions.

Three testing locations were selected for this program: South Florida (Boca Raton), Illinois (Chicago), and Arizona (Phoenix). The 12 repair materials selected for this study were evaluated at each site. Each material was subjected to testing perceived to be of importance in a repair context that would provide basic field-performance information that could be correlated with the results of laboratory testing. Three repairs were accomplished with each of the 12 materials at each exposure site.

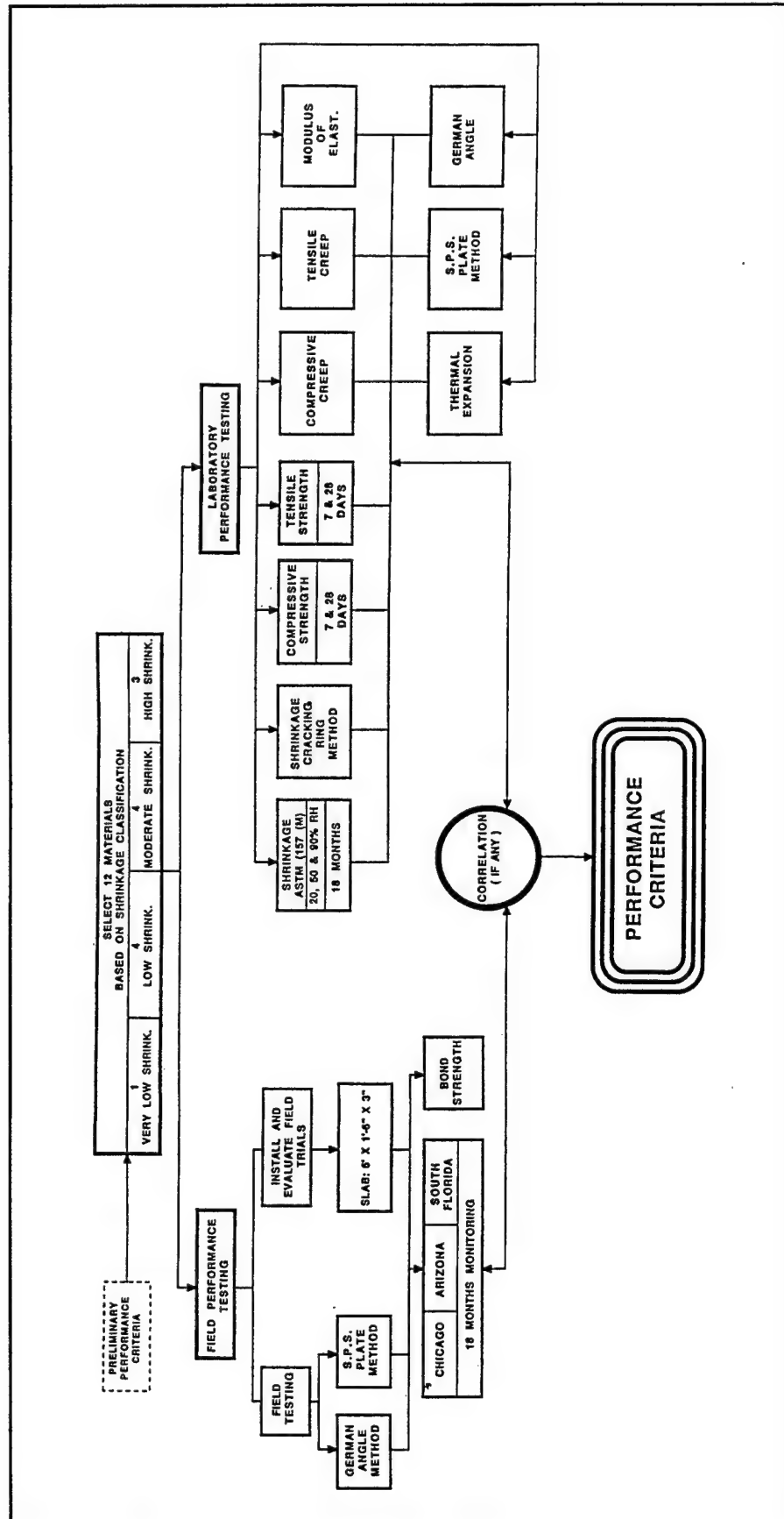


Figure 1. Phase II field and laboratory research program

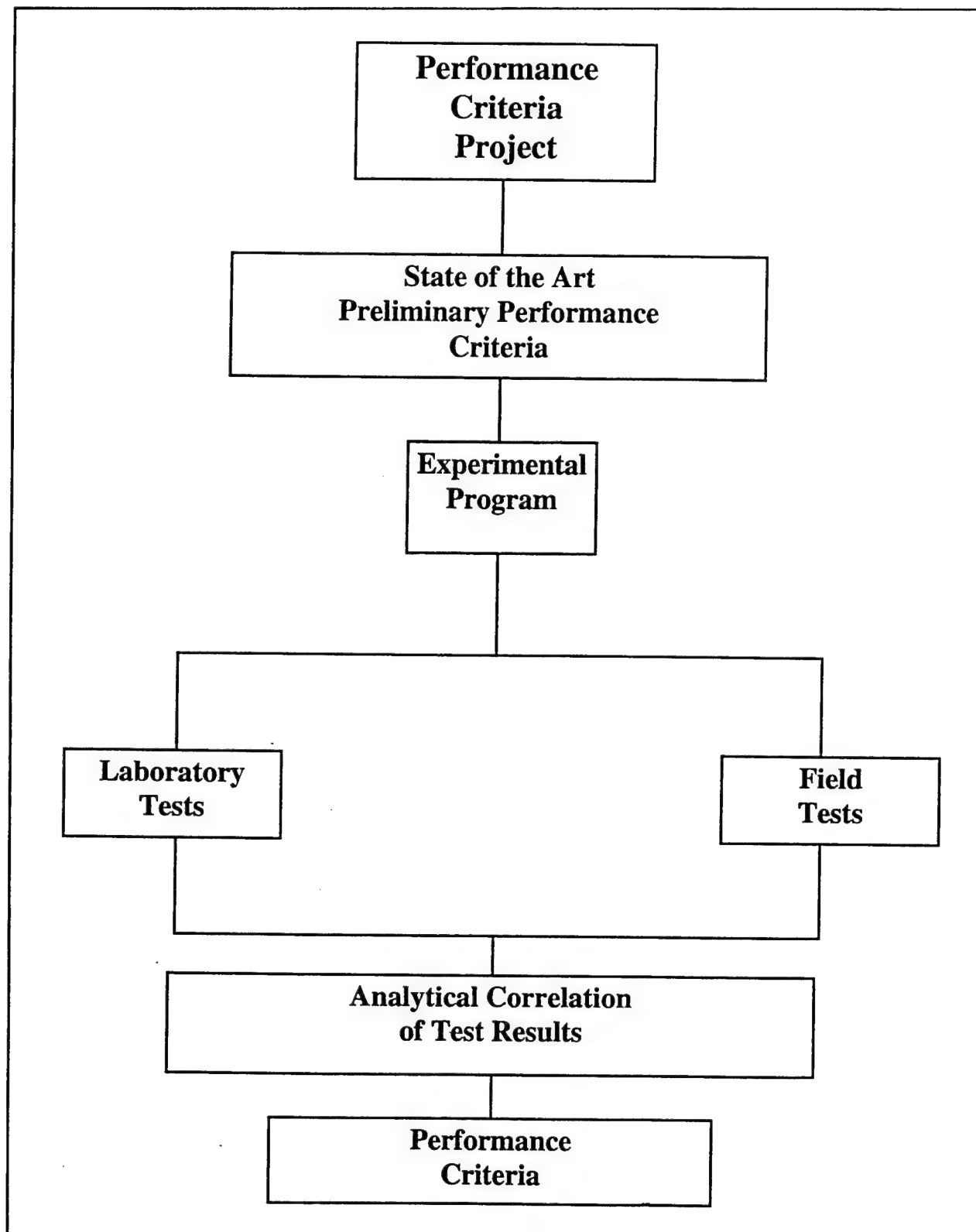


Figure 2. Flowchart of the performance criteria project

2 Field Testing

General

The field-testing program included installation of 12 selected cementitious repair materials in prefabricated concrete slabs (3 for each material at each test site) and monitoring them for an 18-month period following the installation. In addition, the field performance of each material was evaluated in the German Angle Test and the Restrained Volume Change Strain/Stress Indicator (SPS Plate Test). These nonstandard restrained-shrinkage test methods were identified in the Phase I study (Emmons and Vaysburd 1995). A testing protocol for laboratory and field studies was established for each of these non-standard tests to ensure consistency in the testing for all materials.

Field testing was carried out in three areas located in (a) south Florida (Boca Raton), (b) Illinois (Chicago), and (c) Arizona (Phoenix) (Figure 3). These sites were selected to provide a wide variation in exposure conditions ranging from the hot and dry conditions encountered in Arizona, to hot and humid conditions encountered in Florida, to the northern climate of Illinois.

Material Selection

The repair materials were chosen to represent as wide a range in composition, properties, and application technologies as possible. The current product market was surveyed for repair materials. It was desired to include a selection of materials exhibiting a broad range of drying shrinkage. The 12 materials selected represented a range in shrinkage properties from 0.022 to 0.147 percent.

Thirty companies were contacted about including their products in the testing program. The selection of manufacturers to be contacted was based on testing reports, personal contacts, and references from the concrete repair industry. Once a preliminary list of potential materials was developed, the manufacturers were contacted to explain the scope of the research project and to request information on their materials. The drying shrinkage of the materials at 28 days age, as measured by the American Society for Testing and Materials (ASTM) C 157 (1994d), was of particular interest. Some of the firms did not supply the information requested.

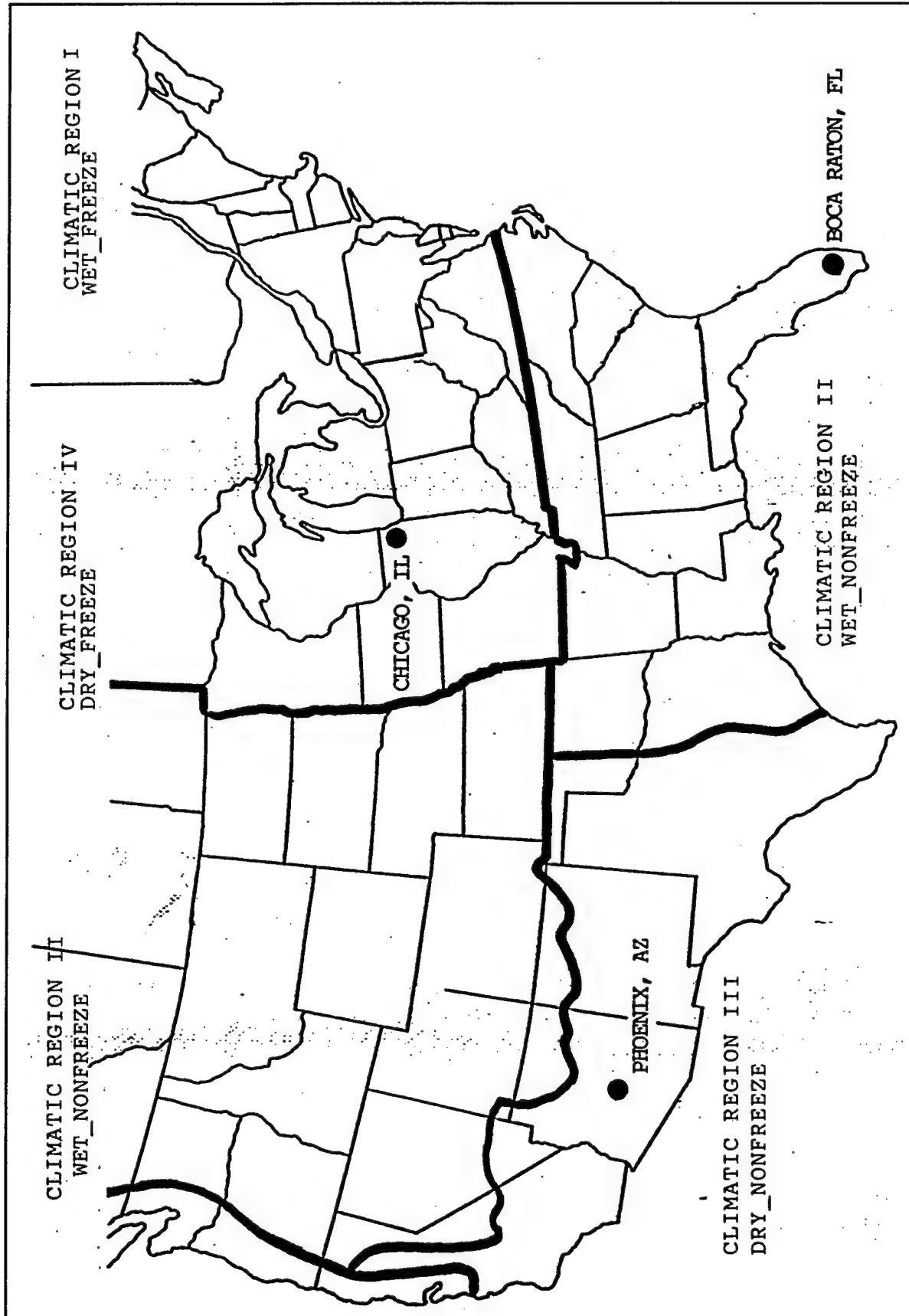


Figure 3. Repair test site locations and climate regions (after Mojab, Patel, and Romine 1993)

Additional letters were sent, and telephone inquiries were made for clarification and to obtain specific information.

The generic types of materials, as classified by the manufacturers, and shrinkage properties are shown in Table 1. It should be noted that 9.5-mm (3/8-in.) nominal maximum size aggregate was used to extend several of the repair mortars in tests reported herein. Additional information on each material is provided in Appendix A. A prepackaged conventional concrete mixture (Material No. 9) was selected as a control material. The materials were shipped to the field-test sites directly from the manufacturers.

Table 1 Material Information		
Code Number	Generic Type	Shrinkage at 28 days, %
1	Cement mortar	0.022
2	Cement concrete	0.048
3	Polymer-modified concrete	0.05
4	Cement concrete	0.05
5	Mortar	0.04
6	Polymer-modified mortar	0.086
7	Polymer-modified mortar	0.07
8	Polymer- and fiber-modified mortar	0.06
9	Portland cement concrete	0.06 ¹
10	Polymer-modified cement mortar	0.093
11	Cement-based mortar	0.075
12	Polymer-modified portland cement mortar	0.147 ²
¹ Data provided by the investigator.		
² Data as tested by Alberta Transportation and Utilities (1987).		

Shortly after the material selection was completed, the production of Material No. 12 (Table 1) was discontinued. A similar material from the same manufacturer was used in the field tests.

Test Slabs

The precast concrete slabs were designed to simulate a concrete surface that had been prepared for repair. The slabs were designed with the center part representing an existing concrete structure cavity that had been prepared to receive a repair material (Figure 4). To approximate the geometric proportions and, in particular, to approximate the surface area/volume ratio of a typical surface repair, a repair thickness of 76 mm (3 in.) was selected. At this thickness, the use of coarse aggregate in the mixture would not introduce unrealistically disproportionate restraint and discontinuity, and also would allow the selection of concrete as a control repair material.

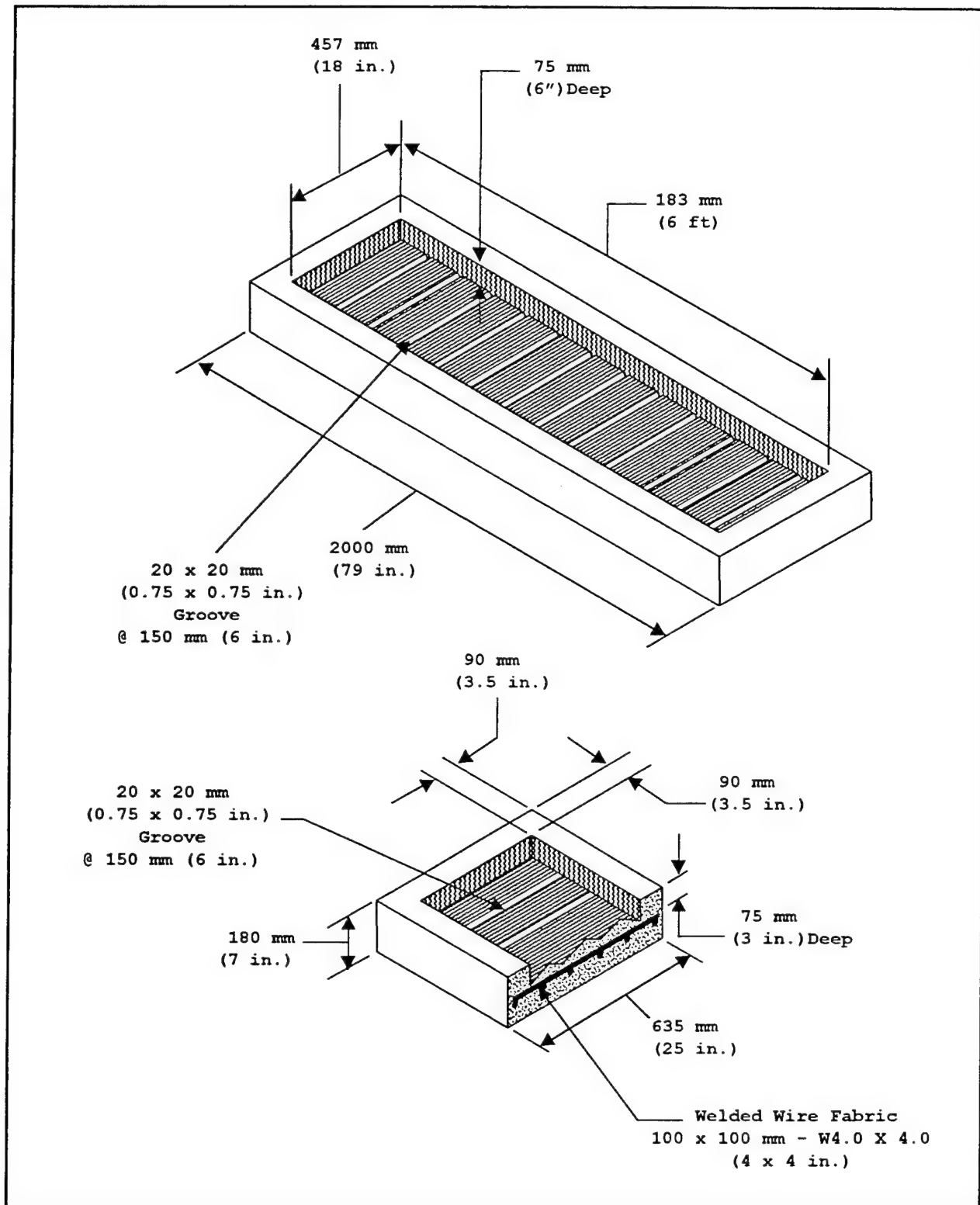


Figure 4. Repair test slab

The profile and preparation of the cavity surface were selected to represent actual concrete surface preparation conditions encountered in the field, as well as restraint conditions to establish the full range of possible behavior. Additional restraint was provided by transverse grooves in the bottom of slabs.

The concrete mixture used in precasting the slabs was proportioned with a 0.42 w/c for a compressive strength of 34 MPa (5,000 psi). Mixture proportions for a 1-m³ (1-yd³) batch were as follows:

Material	1 m ³ (1 yd ³)
Type I Portland Cement	427 kg (720 lb)
Fine Aggregate	678 kg (1,142 lb)
Coarse Aggregate	1,038 kg (1,750 lb)
Air-entraining Admixture	0.26 L (7 oz)
Water-reducing Admixture	2.1 L (56 oz)
Water	180 L (35.9 gal)

Air contents and slumps of the fresh concrete were 4 to 6 percent and 76 to 102 mm (3 to 4 in.), respectively.

Ready-mix concrete was used in fabrication of the test slabs. A total of 126 slabs were fabricated by Back River Supply, Inc., Glyndon, MD, a manufacturer of precast concrete products. A mechanical strain gauge was used to monitor drying shrinkage of the slabs. Results of these measurements indicated that 4 months drying was sufficient for the concrete to attain volume stability. At this point in time, a penetrating sealer was applied thoroughly to all slab surfaces. The surfaces were sealed to minimize the effects of outside moisture movements on expansion and contraction of the slabs during the field testing.

Upon completion of slab preparation (Figure 5), 42 slabs (36 slabs for testing and 6 slabs as spares) were shipped to south Florida, Illinois, and Arizona testing sites.

Experimental Repairs

Each material was used to repair the cavities in three slabs at each test site. The manufacturer's data on materials, mixture proportions, application, and curing along with field observations during casting are included in Appendix A.

The field-testing program included mixing, casting, curing, and monitoring of the repairs. The materials were mixed in standard electric mortar mixers (Figure 6). Immediately prior to placing the repair mixture, the interior cavity was coated with an epoxy bonding compound (Figure 7). Epoxy coating in combination with the silane sealer applied by the slab manufacturer prohibited absorption of water from the repair mixture. This approach provided uniform



Figure 5. Preparing precast concrete test slabs for shipment



Figure 6. Mortar mixer



Figure 7. Application of epoxy bonding compound

conditions for materials tested and allowed only one-dimensional moisture movement to the exposed surface.

Temperature and relative humidity were monitored during the casting operations. In Florida the average temperature varied from 83 to 99.5 °F,¹ and the relative humidity ranged from 69 to 95 percent. In Chicago, the average temperature varied from 72 to 98 °F, and the relative humidity ranged from 45 to 73 percent. In Arizona, the average temperature varied from 49 to 74 °F, and the relative humidity ranged from 38 to 85 percent. Information on placing conditions is summarized in Tables 2 through 4.

The placing, consolidation, finishing, and curing procedures (Figures 8 through 11) were in accordance with manufacturer's recommendations except where otherwise noted. All materials at a given site were placed in the minimum practical time. Minimizing the time interval between individual placements was desirable to attain essentially the same construction conditions, particularly temperature and humidity, thus providing for uniform application conditions.

General observations on the placing and finishing characteristics of the materials are included in Appendix A and summarized in Tables 2 through 4. Material No. 5 presented the most difficulties in placing and finishing because of its very rapid setting characteristics. Based on the manufacturer's

¹ To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$.

Table 2 Material Application Information - Florida					
Material No.	Placement Information				Comments
	Date of Placement	Time (beginning of mixing)	Temperature, °F	RH %	
1	08/04/94	1:00 PM	96.4	78	Very good workability, easy to finish.
2	08/02/94	3:30 PM	95	83	Good workability, easy to finish.
3	08/02/94	8:18 AM	83	95	Easy to finish.
4	08/03/94	8:12 AM	85.5	79	User-friendly material.
5 ¹	08/01/94	9:45 AM	90	69	Very fast-set material. High heat of hydration. Material and slab cracked. Figures 12 and 13.
6	08/02/94	11:00 AM	88	72	Very short finishing time. Plastic shrinkage cracks in one repair.
7	08/04/94	11:00 AM	85	95	Very fast set. Hard to finish.
8	08/01/94	12:50 PM	95	60	Difficult to place.
9	08/19/94	9:30 AM	93	74	Good workability conventional concrete.
10	08/03/94	11:15 AM	83	95	Very cohesive, sticky, difficult to finish. Figure 14.
11	08/04/94	12:10 PM	99.5	72	User-friendly material.
12	08/05/94	8:20 AM	85	81	Difficult to finish.
¹ Not expanded with aggregates.					

Table 3
Material Application Information - Illinois

Material No.	Placement Information				Comments
	Date of Placement	Time (beginning of mixing)	Temperature °F	RH %	
1	09/14/94	2:00 PM	90	58	Excellent workability.
2	09/14/94	10:30 AM	83	68	Easy to mix, place, and finish.
3	09/13/94	9:35 AM	72	67	Easy to finish.
4	09/13/94	1:50 PM	97	47	Easy to work material. Outgassing noted. Figure 15.
5	09/14/94	9:00 AM	80	73	Aggregate was prewetted with part of mixing water. High heat of hydration.
6	09/12/94	11:30 AM	93	48	Short finishing time. Becomes increasingly dry.
7	09/13/94	10:55 AM	72	59	Very fast set. Could not finish Repairs A and B. Added ice and increased water for Repair C.
8	09/12/94	9:50 AM	78	66	Very difficult to mix and place. Had to be tamped. Figure 16.
9	09/12/94	2:00 PM	96	50	Good workability conventional concrete.
10	09/13/94	3:00 PM	98	45	Very cohesive, self-leveling, sticky, difficult to finish. Surface tears noted.
11	09/12/94	8:45 AM	79	67	Good workability, easily placed and finished.
12	09/14/94	11:45 AM	87.5	62	Difficult to finish. Figure 17.

Table 4
Material Application Information - Arizona

Material No.	Placement Information				Comments
	Date of Placement	Time (beginning of mixing)	Temperature °F	RH %	
1	12/06/94	2:30 PM	74	52	User-friendly material.
2	12/07/94	12:40 PM	70	45	Good workability, easy to finish.
3	12/06/94	11:30 AM	62	74	Easy to finish.
4	12/07/94	10:40 AM	68	61	Material appears to expand, and gasses are released leaving holes in the finished surface. Figure 15.
5	12/08/94	10:15 AM	66	53	Aggregate was prewetted. High heat of hydration.
6	12/06/94	1:30 PM	64	68	Very dry mixture.
7	12/06/94	10:00 AM	60	85	Very difficult to finish.
8	12/07/94	9:30 AM	62	68	Difficult to work with.
9	12/08/94	9:10 AM	49	62	Good workability conventional concrete.
10	12/08/94	2:00 PM	66	38	Material is very dry after mixing, then becomes workable.
11	12/08/94	1:00 PM	64	48	Easy to work with.
12	12/07/94	1:50 PM	67	54	Not easy to finish.



Figure 8. Placement of material



Figure 9. Vibration



Figure 10. Finishing

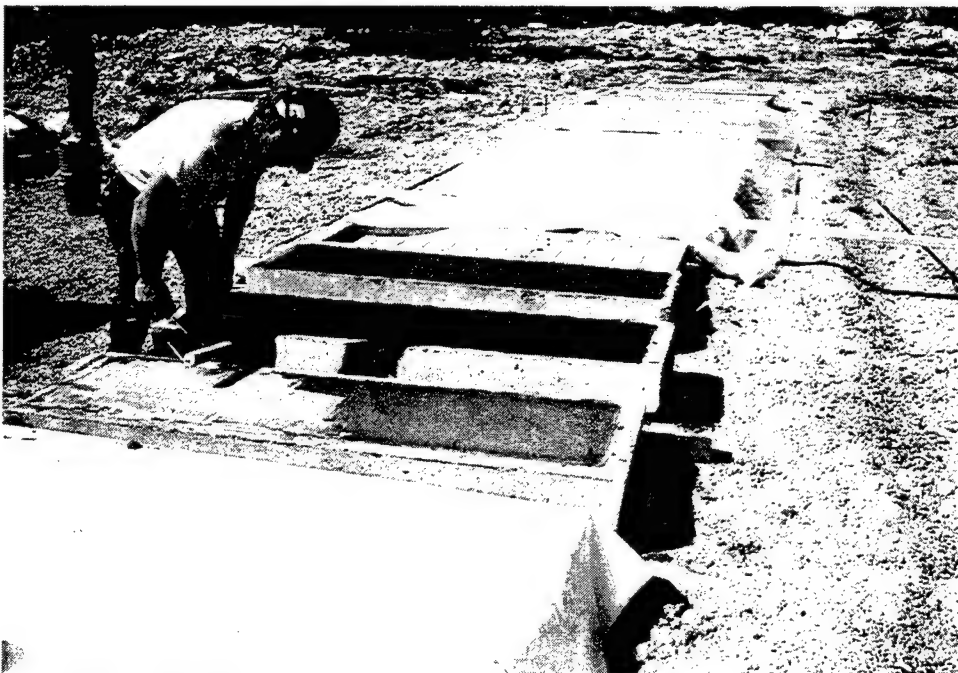


Figure 11. Curing

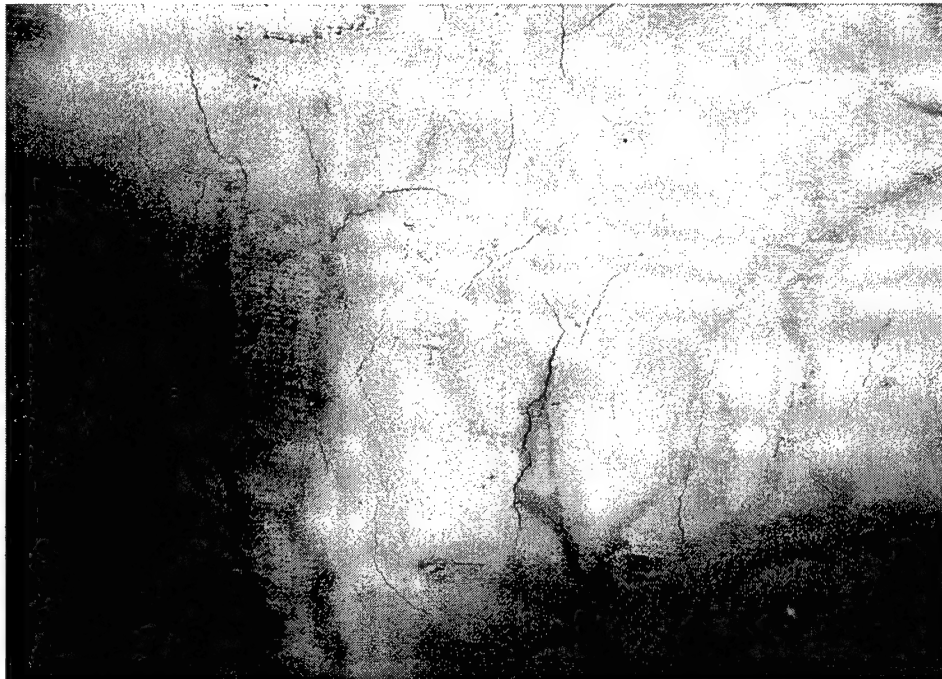


Figure 12. Severe cracking, Material No. 5 (Florida)



Figure 13. Cracks in the cavity walls, Material No. 5 (Florida)



Figure 14. Very cohesive material (No. 10), sticky, difficult to finish (Florida)



Figure 15. Outgassing noted after finishing of Material No. 4 (Illinois and Arizona)

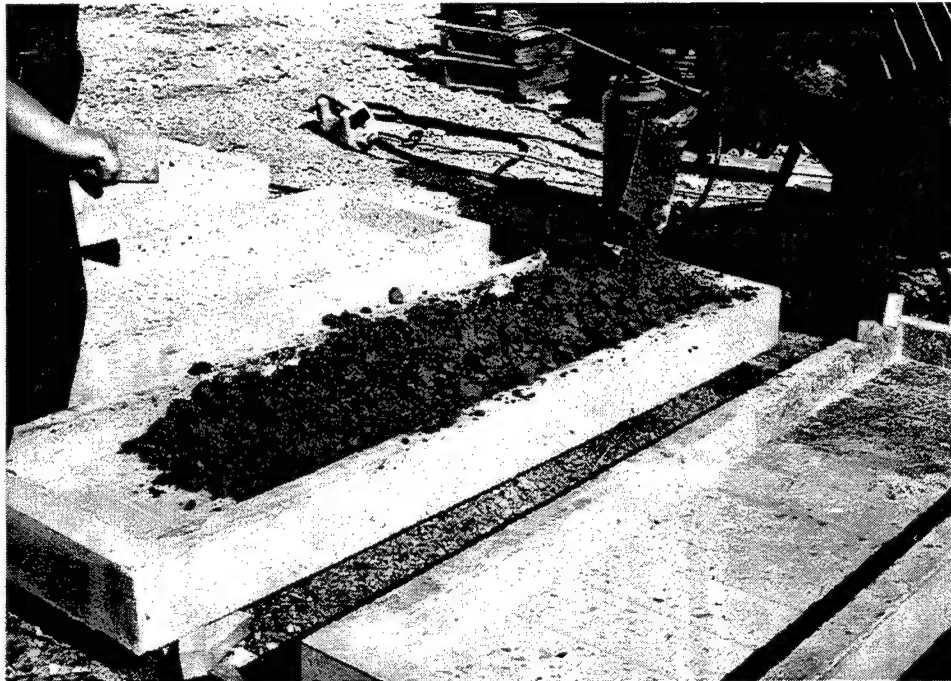


Figure 16. Example of a material (No. 8) that was very difficult to place and finish (Illinois)

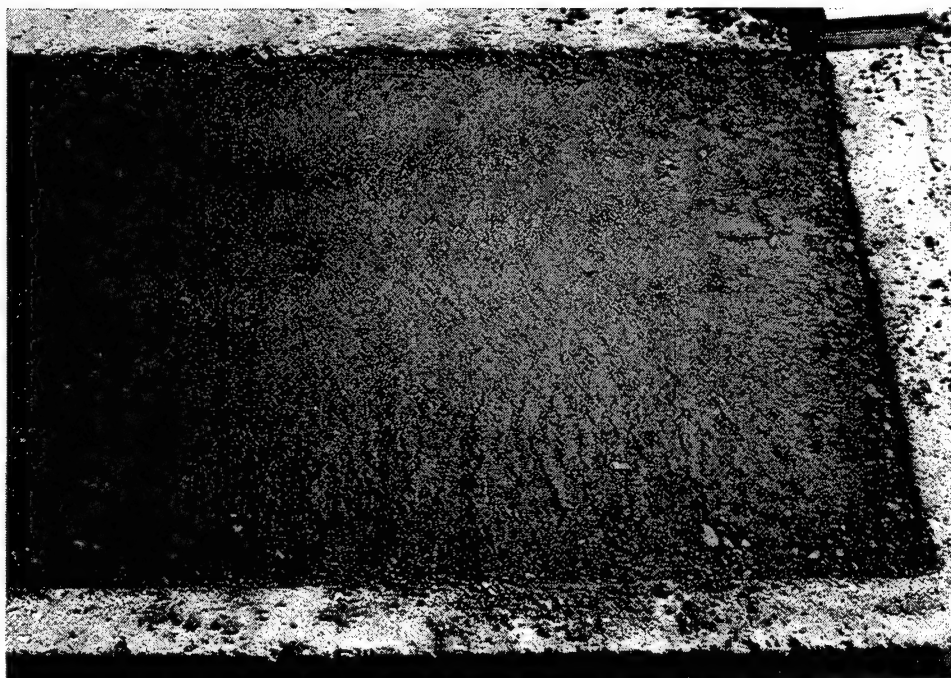


Figure 17. Material (No. 12) that was not easy to finish (Illinois)

recommendations, the mixture was not extended with aggregate in the Florida tests. Despite immediate sprinkling with water after finishing, early age, plastic-shrinkage cracking occurred in each of the three repairs (Figure 12).

The rapid setting of Material No. 5 was accompanied by a high heat of hydration. Expansion of the repair material associated with the high temperature rise was sufficient to cause cracking in the precast concrete cavity walls (Figure 13). Subsequent cooling and restrained contraction of the repair material may have contributed to the early age cracking observed. Consequently, the manufacturer recommended that the mixture be extended with coarse aggregate for the remaining tests. Early age cracking in Repair 6C was also attributed to plastic shrinkage.

Restrained Shrinkage Tests

Two types of nonstandard tests were conducted under field-exposure conditions to evaluate restrained volume changes and cracking potential of the repair materials. The Restrained Volume Change Strain/Stress Indicator (SPS Plate Test) and German Angle Test are described in the following:

SPS Plate Test

This restrained volume change test (Figure 18) had been recommended for further study in the Phase I program (Emmons and Vaysburd 1995). The test specimen is a nominal 51- by 102- by 1,321-mm (2- by 4- by 52-in.) beam.

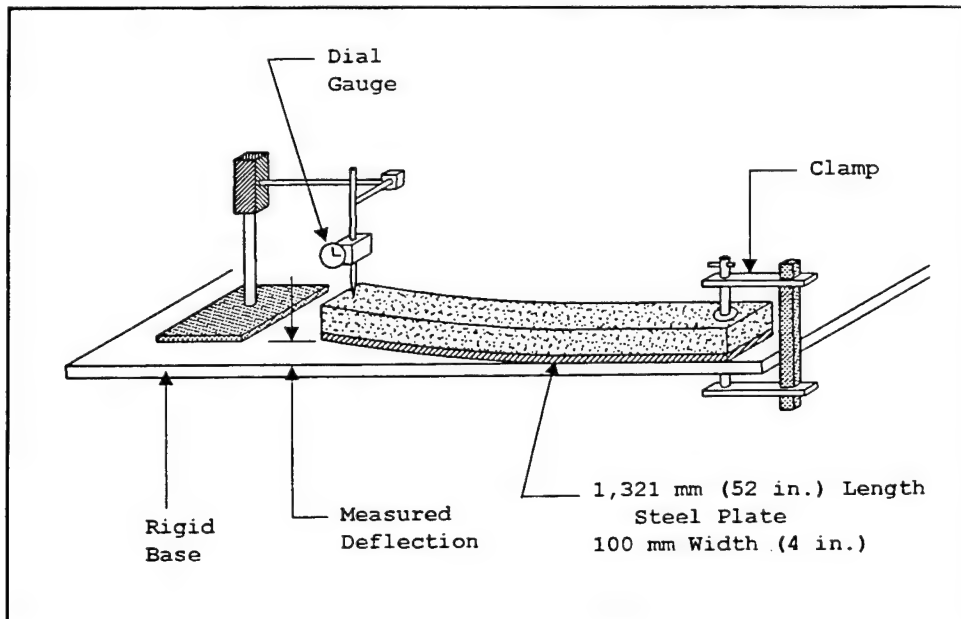


Figure 18. Schematic of restrained volume change strain/stress indicator (SPS Plate Test)

The repair material is cast against a thin steel plate on the bottom of the form. The plate has a layer of epoxy with broadcasted sand grit to improve the bond between the material and steel plate.

The specimen is supported by a rigid steel channel. It is fixed at one end, and the other is free to move. Casting of the specimens is shown in Figures 19 and 20. Photographs of the specimens during monitoring are shown in Figures 21 and 22. As the material expands or contracts in response to moisture and temperature changes, the free end deflects accordingly (Figure 23). Deflection of the unrestrained end of the specimen is measured at three marks along the specimen width (Figure 24).

German Angle Test

This test had been recommended in the Phase I program (Emmons and Vaysburd 1995) as a candidate for the restrained shrinkage test. The test consists of filling a steel angle (Figure 25) with a repair material. The interior surface of the angle was initially thoroughly cleaned with a degreaser. An epoxy bonding compound was applied to the angle immediately prior to casting the specimen. Following casting, the test specimens were monitored for cracking under field-exposure conditions. Typical test specimens are shown in Figures 26 through 28.

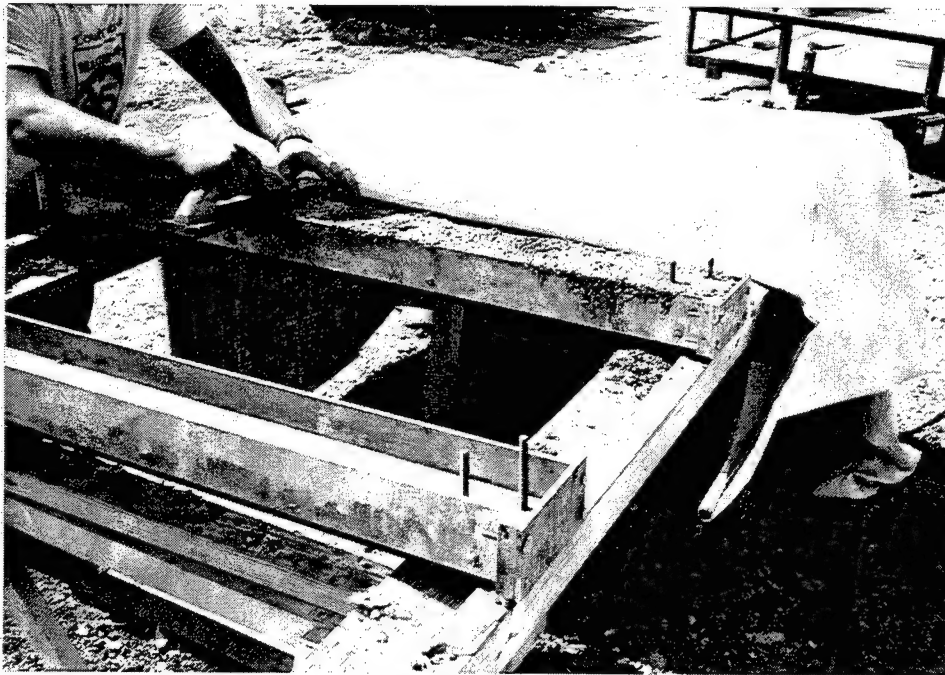


Figure 19. Fabrication of SPS Plate specimen



Figure 20. SPS Plate Test specimens prior to curing



Figure 21. SPS Plate Test (Illinois)



Figure 22. SPS Plate Test (Arizona)

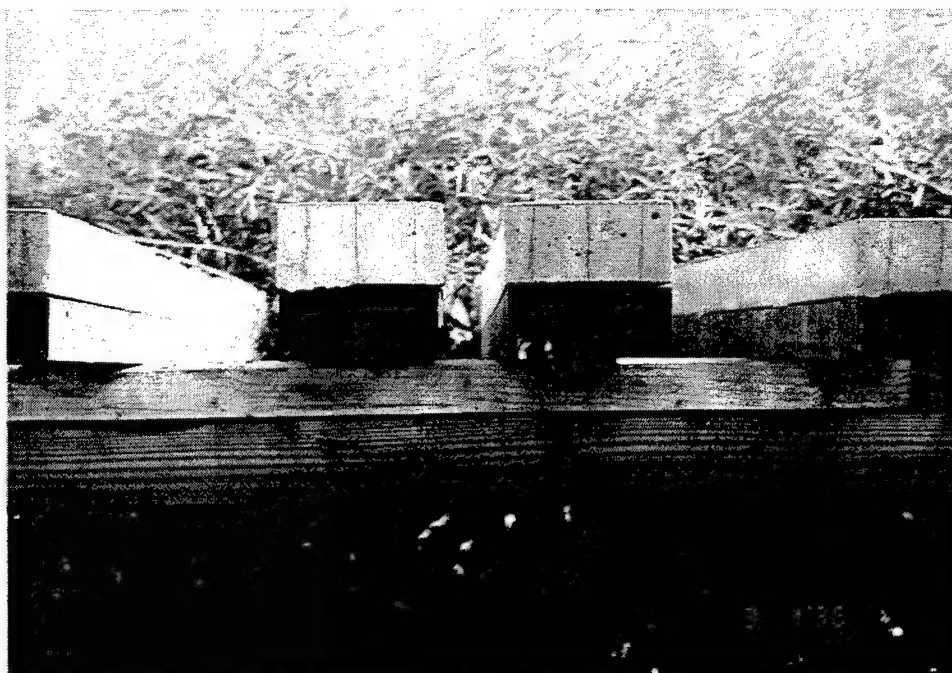


Figure 23. Deflection of unrestrained ends of SPS Plate Test specimens

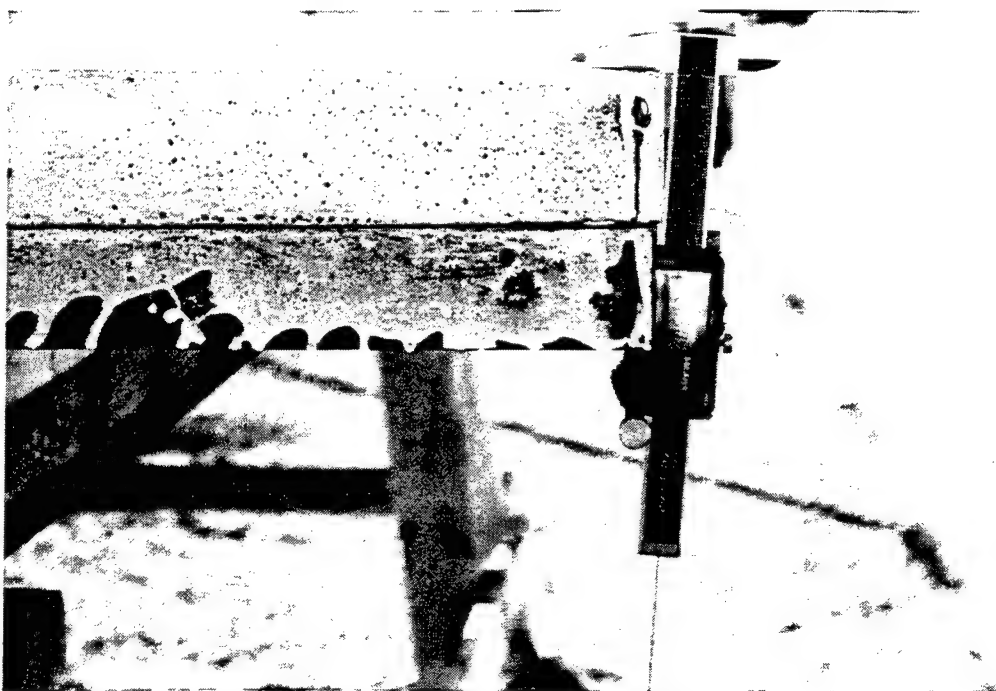


Figure 24. Tip deflection measurement, SPS Plate Test

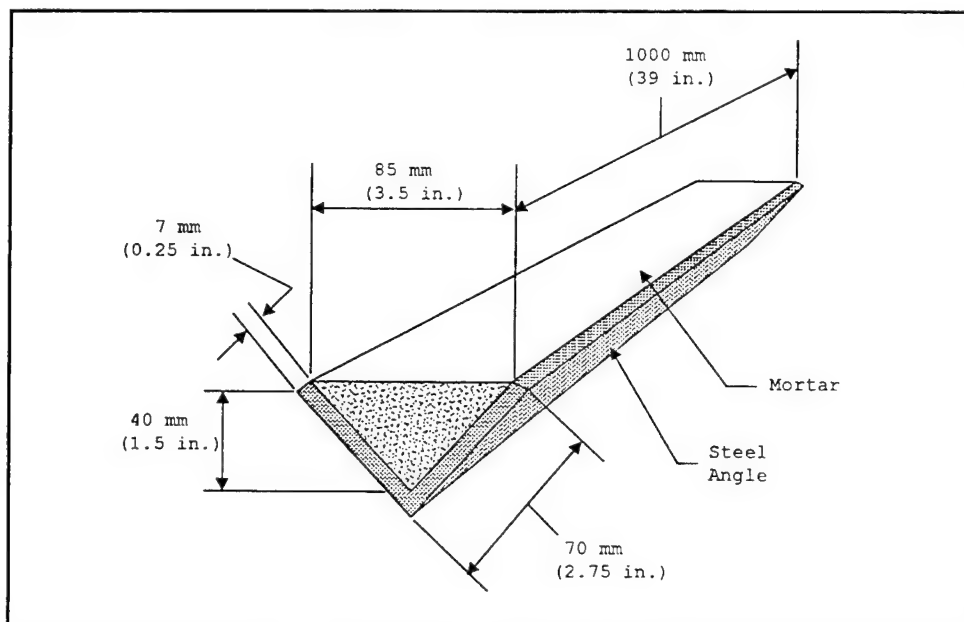


Figure 25. German Angle Test specimen

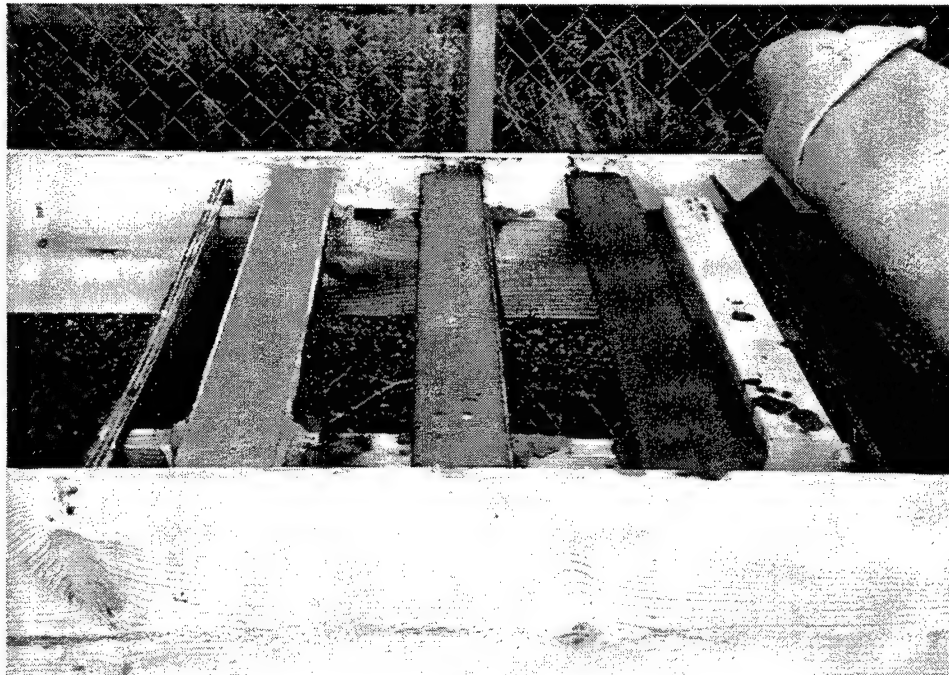


Figure 26. German Angle field test



Figure 27. German Angle Test specimens (Florida)



Figure 28. German Angle Test specimens (Arizona)

3 Test Results

General

The results of field tests conducted as part of the Phase II program are summarized in this chapter. Where appropriate, selected comparisons of measured and monitored material behavior are provided. The data included in this chapter are based on test results and performance observations on selected concrete repair materials as delivered to each test site by the respective material manufacturers at the time of testing. Accordingly, the data may not always be representative of the materials currently available.

The observations, findings, and discussions presented in this chapter are strictly directed toward developing performance criteria and are not intended to credit or discredit any product. This section includes the relative ranking of the materials in different field tests and an overall ranking. This ranking will be compared with the ranking based on the results of the laboratory tests. It should be noted that the relative ranking does not reflect the magnitude of the differences in performance between the repair materials, and it is presented only for correlation of material performance in field and laboratory tests.

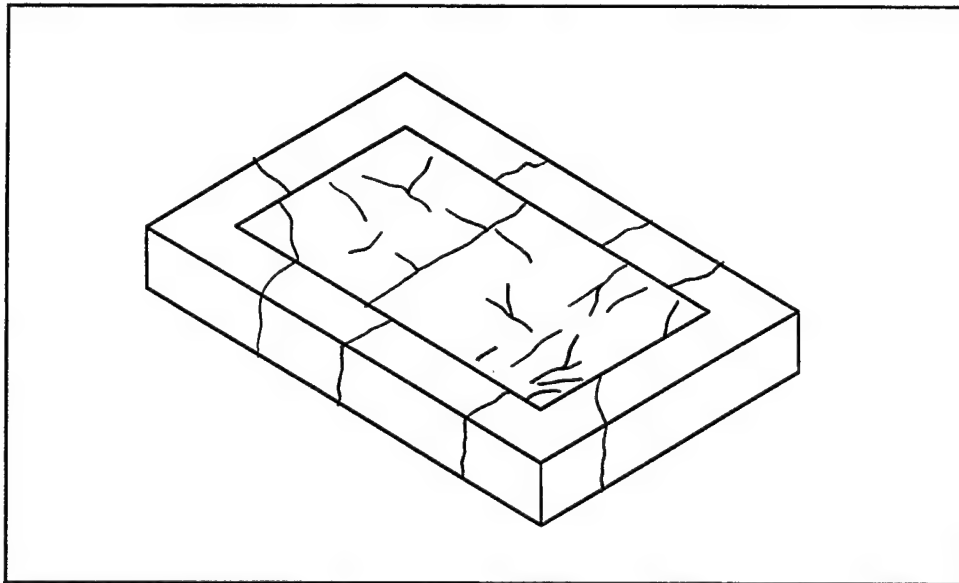
Experimental Repairs

This section describes the results of field tests and monitoring of crack development conducted during Phase II. Performance of the repairs depends not only on dimensional compatibility properties of the materials used, but on adequate technological procedures, i.e., correct mixture proportions, placing, finishing, and curing operations. The manufacturer's recommendations were followed as a rule; only in those cases where the mixture was absolutely nonworkable were some adjustments made to the water content. As described earlier, this part of the testing program essentially consisted of repairing cavities in precast concrete slabs. Each material was used in three repairs at each testing site. Once the repair materials were placed and cured, they were monitored periodically to determine their performance, particularly in regard to cracking.

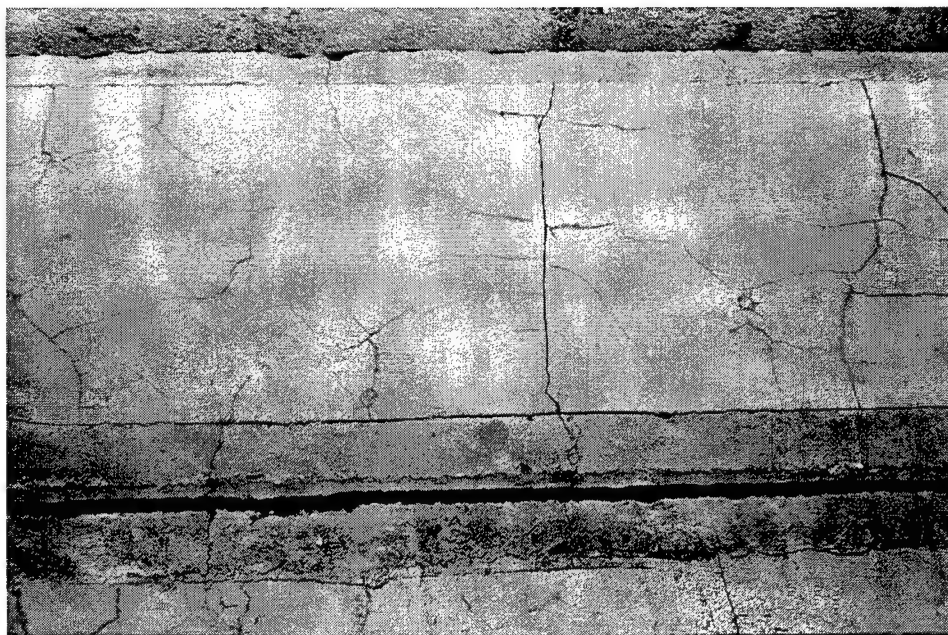
An initial inspection of the repairs was performed within 1 day of completion of curing at each site. Subsequent inspections were generally performed once a week for 6 weeks, then once a month for 7 months, and then once every 2 months during a 10-month period. A total of 19 evaluations were performed in Florida, 18 in Illinois, and 20 in Arizona. A detailed monitoring schedule is given in Appendix B. The evaluation consisted primarily of a visual inspection of the repair surfaces. The different types of cracking and other distresses and the severity of these were recorded.

A significant amount of data were collected during testing at the three sites to monitor the performance of the experimental repairs. Results of the performance monitoring are shown in Tables 5 through 7 and summarized in Table 8. The relative ranking of material performance is shown in Table 9.

Table 5 Results of Repair Monitoring - Florida				
Material No.	Date of Placement	Observations		
		Repair A	Repair B	Repair C
1	08/04/94	No cracks.	No cracks.	No cracks.
2	08/02/94	No cracks.	No cracks.	No cracks.
3	08/02/94	No cracks.	No cracks.	No cracks.
4	08/03/94	No cracks.	No cracks.	No cracks.
5	08/01/94	Extensive cracking of repair and precast slab noted in first inspection (7 days age). More cracks noted at 70 and 105 days. Figure 29.	Extensive cracking of repair and precast slab noted during first inspection (7 days age). More cracks noted at 70 and 105 days. Figure 30.	Extensive cracking of repair and precast slab noted during first inspection (7 days age). More cracks noted at 70 and 105 days. Figure 31.
6	08/02/94	No cracks.	No cracks.	Cracking noted first inspection (6 days age). Edge debonding noted at 440 days. Figure 32.
7	08/04/94	Very fine surface crazing.	Very fine surface crazing.	Very fine surface crazing.
8	08/01/94	Fine surface crazing.	Fine surface crazing.	Fine surface crazing. Figure 33.
9	08/19/94	Minor surface crazing.	No cracks.	No cracks.
10	08/03/94	Very fine surface crazing in repair and cracking in precast form noted at 260 days.	Very fine surface crazing in repair and cracking in precast form noted at 260 days.	Very fine surface crazing in repair and cracking in precast form noted at 260 days.
11	08/04/94	No cracks.	No cracks.	No cracks.
12	08/05/94	No cracks.	No cracks.	No cracks.

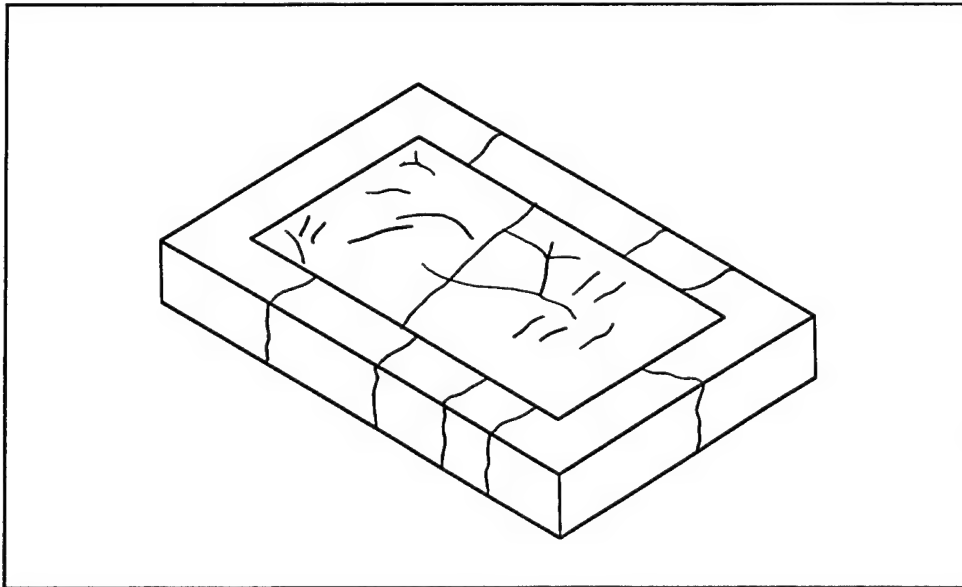


a. Schematic

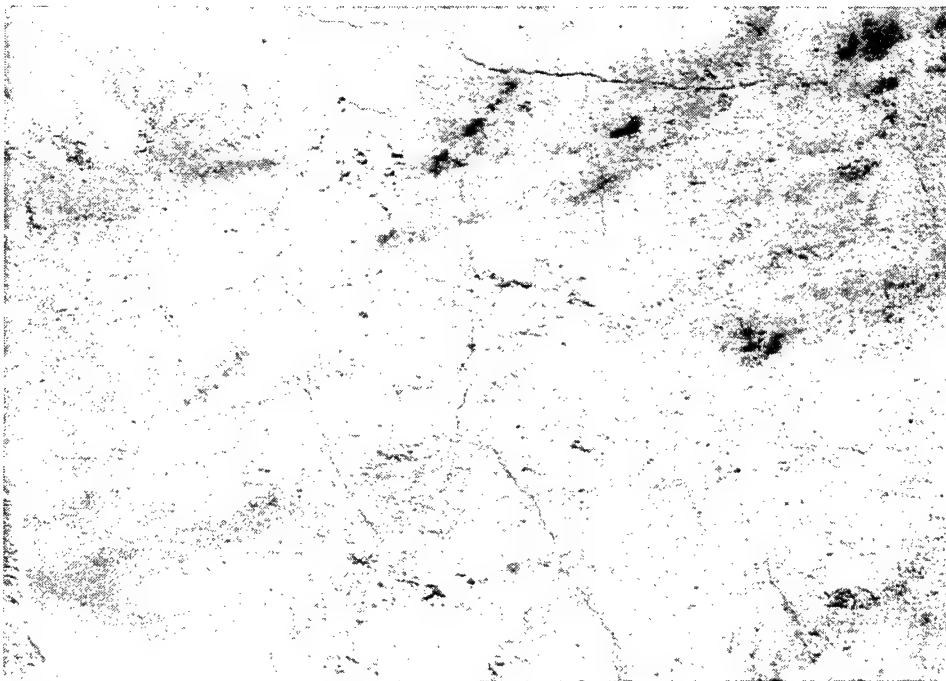


b. Photograph

Figure 29. Cracking of Material No. 5A (Florida)

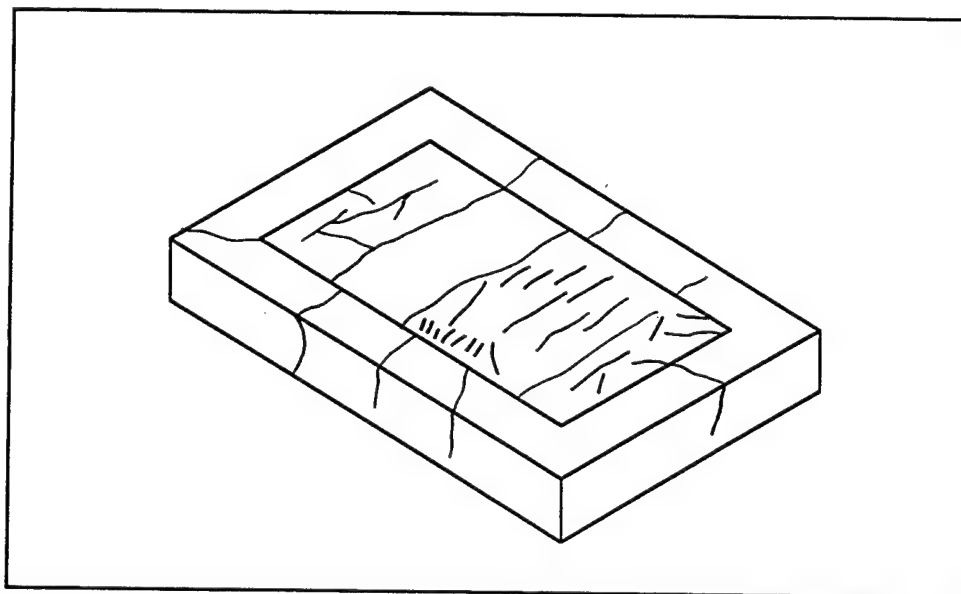


a. Schematic

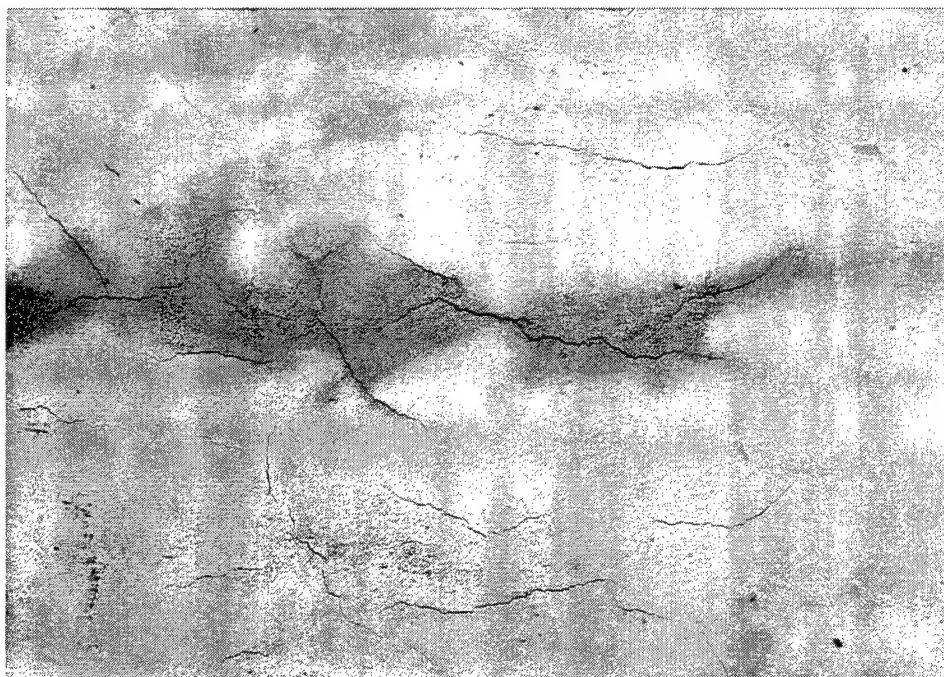


b. Photograph

Figure 30. Cracking of Material No. 5B (Florida)

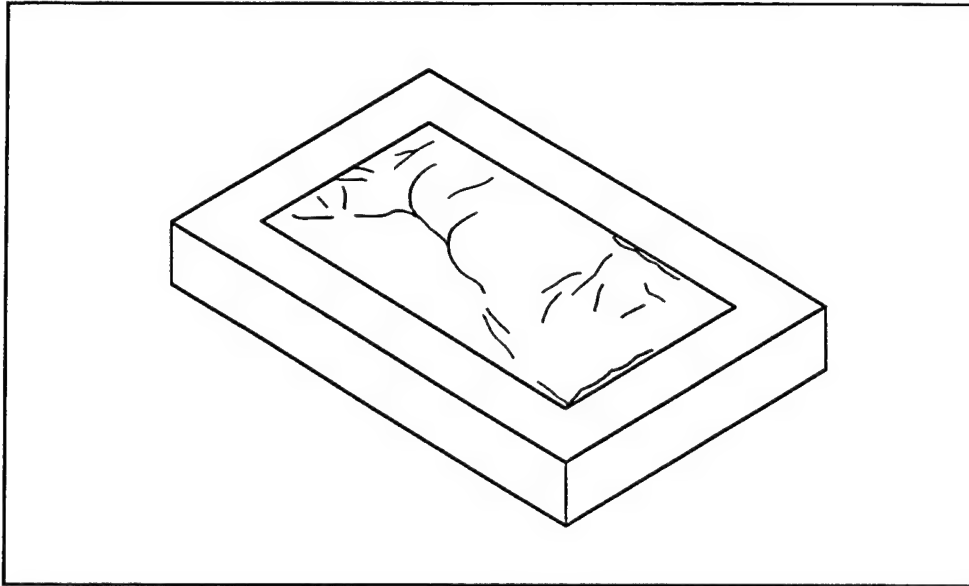


a. Schematic

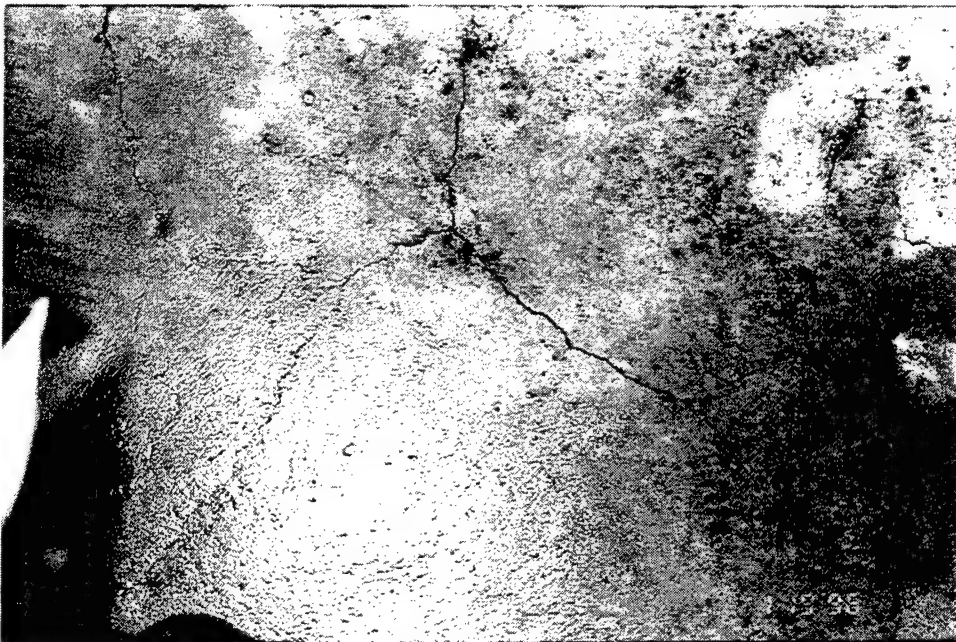


b. Photograph

Figure 31. Cracking of Material No. 5C (Florida)



a. Schematic



b. Photograph

Figure 32. Cracking of Material No. 6C (Florida)

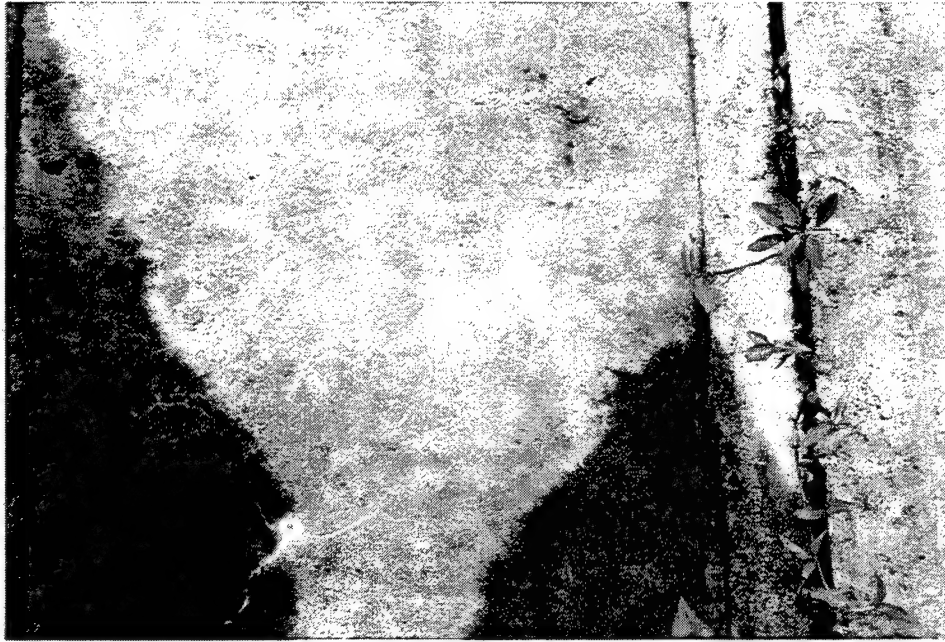
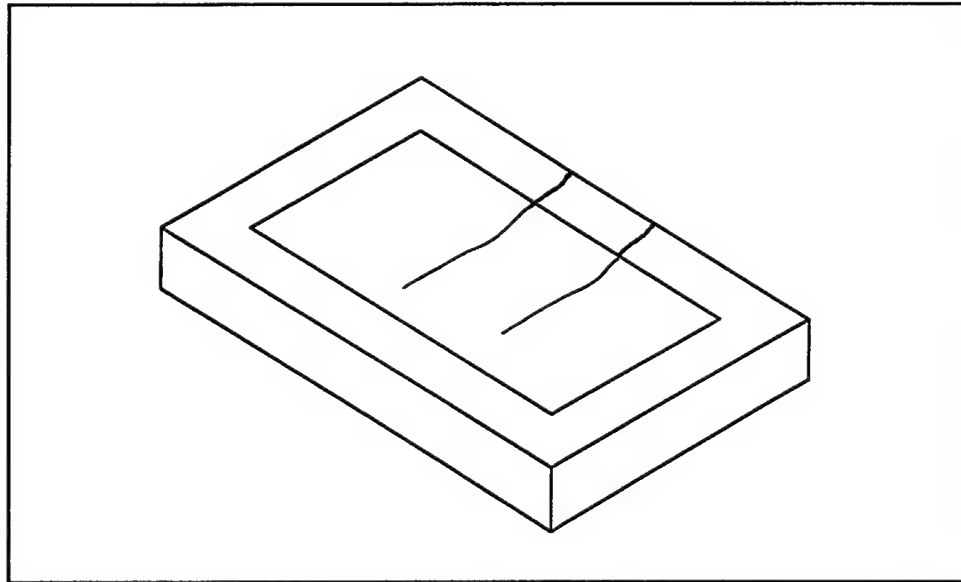


Figure 33. Surface crazing of Material No. 8 (Florida)

Table 6 Results of Repair Monitoring - Illinois				
Material No.	Date of Placement	Observations		
		Repair A	Repair B	Repair C
1	09/14/94	No cracks.	No cracks.	No cracks.
2	09/14/94	No cracks.	No cracks.	Surface crazing
3	09/14/94	No cracks.	No cracks.	No cracks.
4	09/13/94	No cracks.	No cracks.	No cracks.
5	09/14/94	Minor surface crazing. Cracks in concrete slab walls.	Minor surface crazing. Cracks in concrete slab walls.	Minor surface crazing. Cracks in concrete slab walls. Two transverse cracks noted at 560 days. Figure 34.
6	09/12/94	Few fine isolated surface cracks noted at 500 days age.	No cracks.	Few fine isolated surface cracks noted at 560 days age.
7	09/13/94	Unfinished, raveled surface precluded crack observation.	Unfinished, raveled surface precluded crack observation.	Surface crazing noted at 14 days. Figure 35.
8	09/12/94	No cracks.	No cracks.	No cracks.
9	09/12/94	No cracks.	No cracks.	No cracks.
10	09/13/94	Extensive pattern cracking noted at 560 days.	Light pattern cracking noted at 560 days.	Light pattern cracking noted at 560 days. Figure 36.
11	09/12/94	No cracks.	No cracks.	No cracks.
12	09/14/94	Surface deterioration. Figure 37.	No cracks.	No cracks.



a. Schematic



b. Photograph

Figure 34. Cracking of Material No. 5C (Illinois)

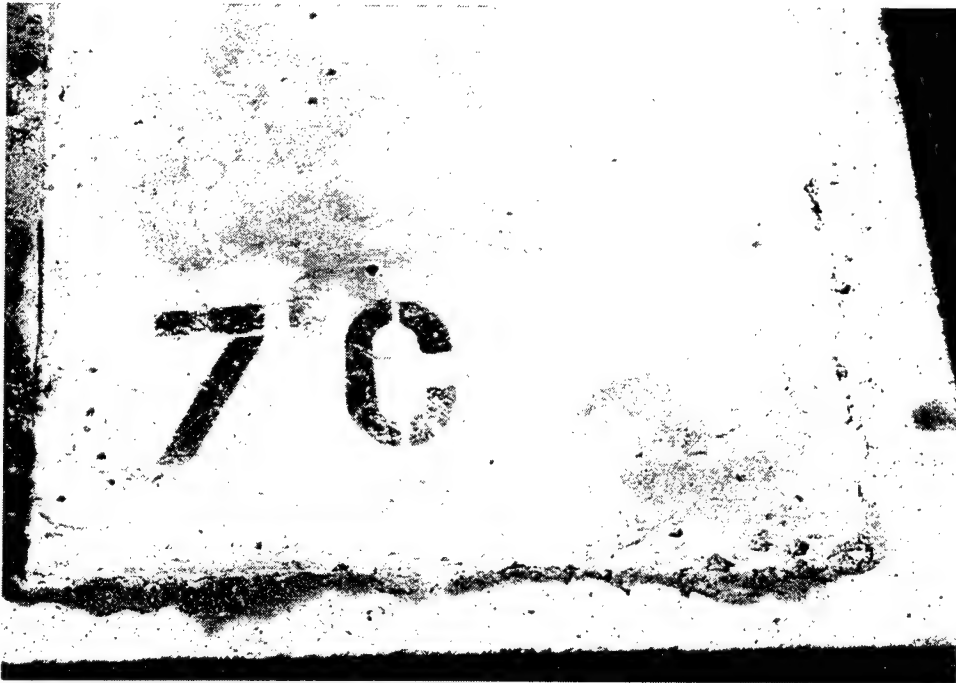


Figure 35. Surface crazing of Material No. 7C (Illinois)

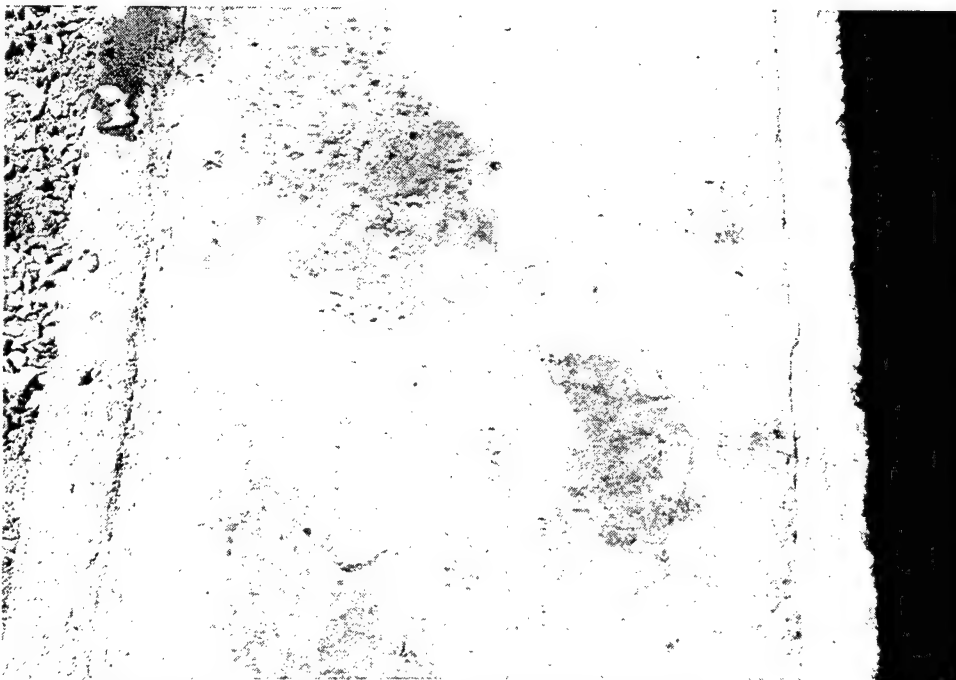


Figure 36. Pattern cracking of Material No. 10 (Illinois)

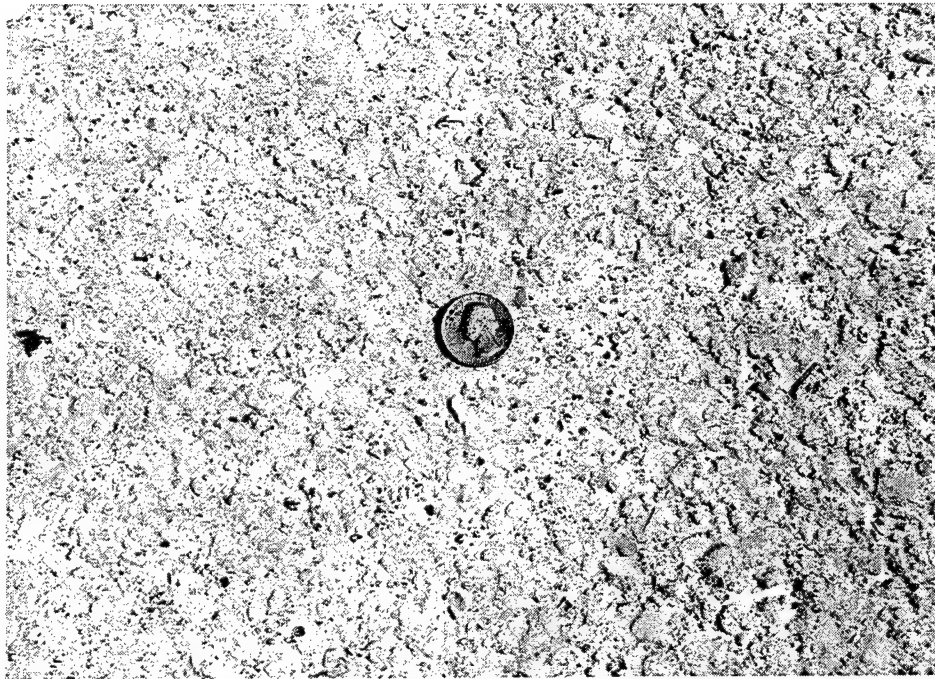


Figure 37. Surface deterioration of Material No. 12C (Illinois)

Table 7
Results of Repair Monitoring - Arizona

Material No.	Date of Placement	Observations		
		Repair A	Repair B	Repair C
1	12/06/94	No cracks.	No cracks.	No cracks.
2	12/07/94	Four edge cracks noted at 7 days. Figure 38.	One edge crack noted at 7 days.	Seven edge cracks noted at 7 days. Two additional cracks noted at 14 days. One additional crack noted at 28 days.
3	12/06/94	Surface checking noted at 200 days.	One transverse crack noted at 170 days. Figure 39.	Surface checking noted at 200 days.
4	12/07/94	No cracks.	No cracks.	No cracks.
5	12/08/94	No cracks.	One edge crack noted at 7 days. One transverse crack noted at 500 days. Figure 40.	One edge crack noted at 7 days.
6	12/06/94	One edge crack noted at 7 days. One transverse crack noted at 620 days. Figure 41a.	Six edge cracks noted at 7 days. Figure 41b.	Four edge cracks noted at 7 days. Figure 41c.
7	12/06/94	Not cast.	Surface checking noted at 7 days. Three short transverse cracks noted at 135 days. Figure 42.	Surface checking noted at 7 days age. One crack noted at 7 days. Ten additional cracks noted 135 days. Figure 42.
8	12/07/94	No cracks.	No cracks.	No cracks.
9	12/08/94	No cracks.	No cracks.	No cracks.
10	12/08/94	Thirty-nine cracks noted at 7 days. One additional crack noted at 21 days. Four additional cracks noted at 35 days. Figure 43a.	Six cracks noted at 7 days. Figure 43b.	Two cracks noted at 7 days. Thirteen additional cracks noted at 170 days. Three additional cracks noted at 200 days. Four additional cracks noted at 240 days. Two additional cracks noted at 260 days. Figures 43c and 44.
11	12/08/94	No cracks.	No cracks.	No cracks.
12	12/07/94	No cracks.	No cracks.	No cracks.

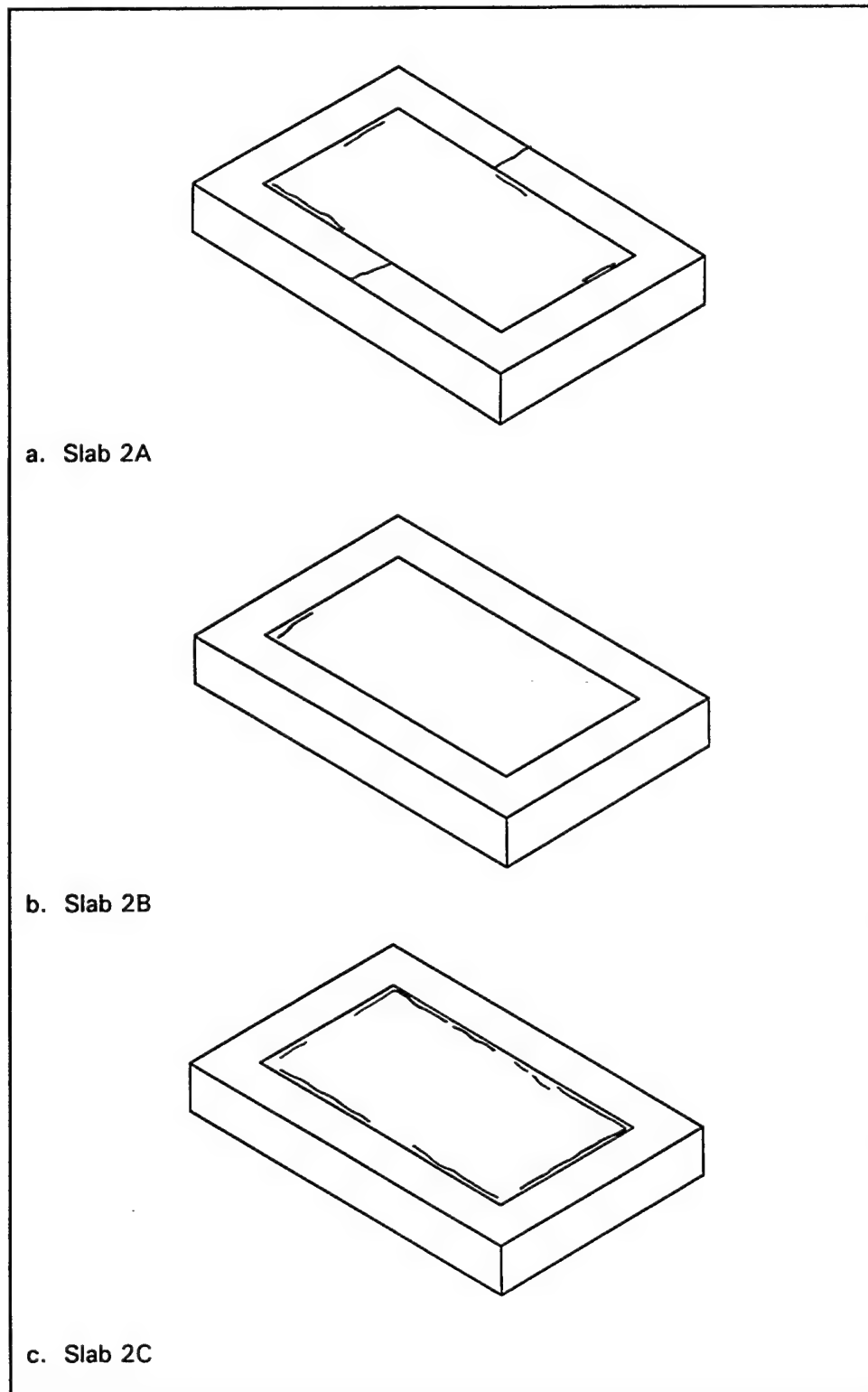


Figure 38. Edge cracking associated with Material No. 2 (Arizona)

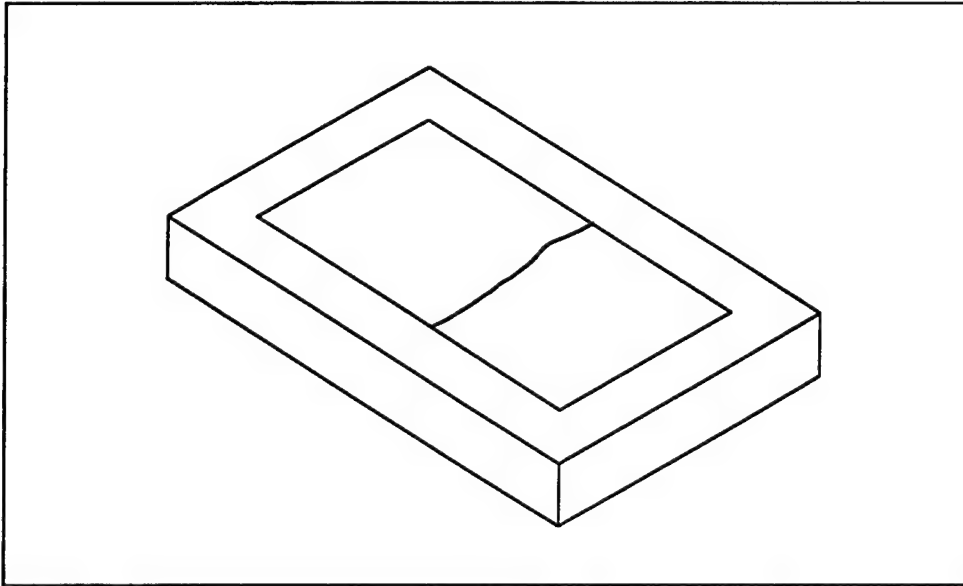


Figure 39. Cracking of Material No. 3B (Arizona)

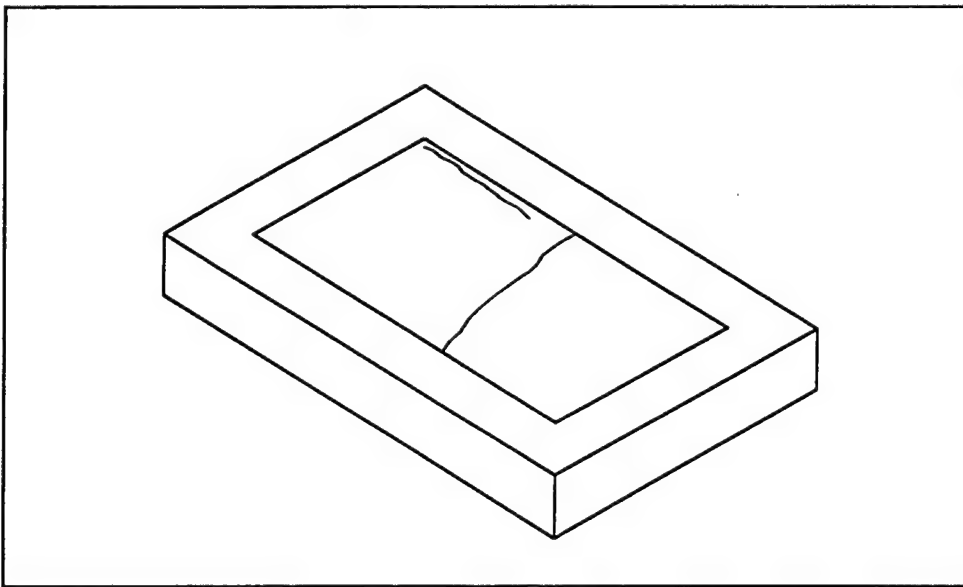


Figure 40. Cracking of Material No. 5B (Arizona)

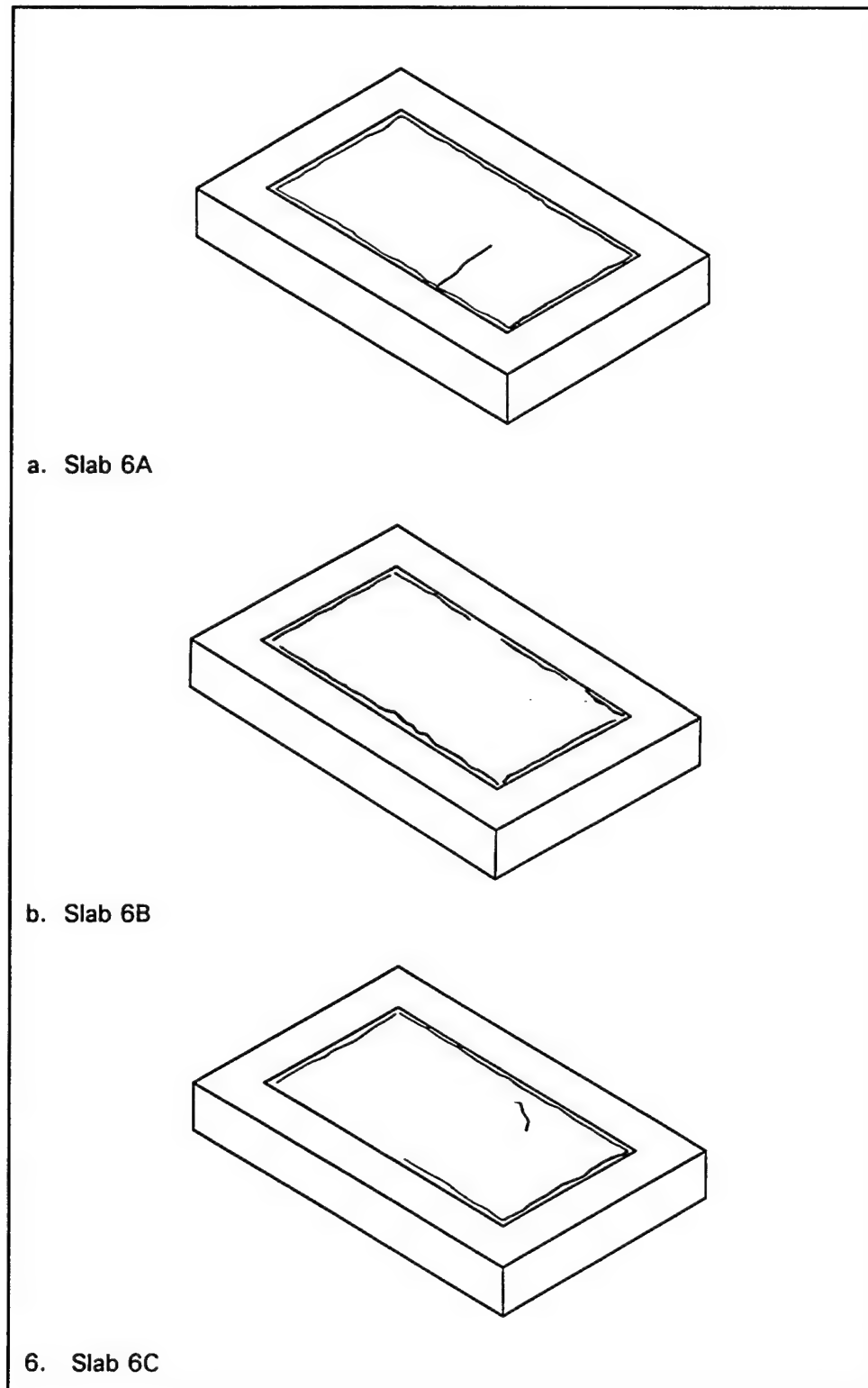


Figure 41. Cracking of Material No. 6 (Arizona)

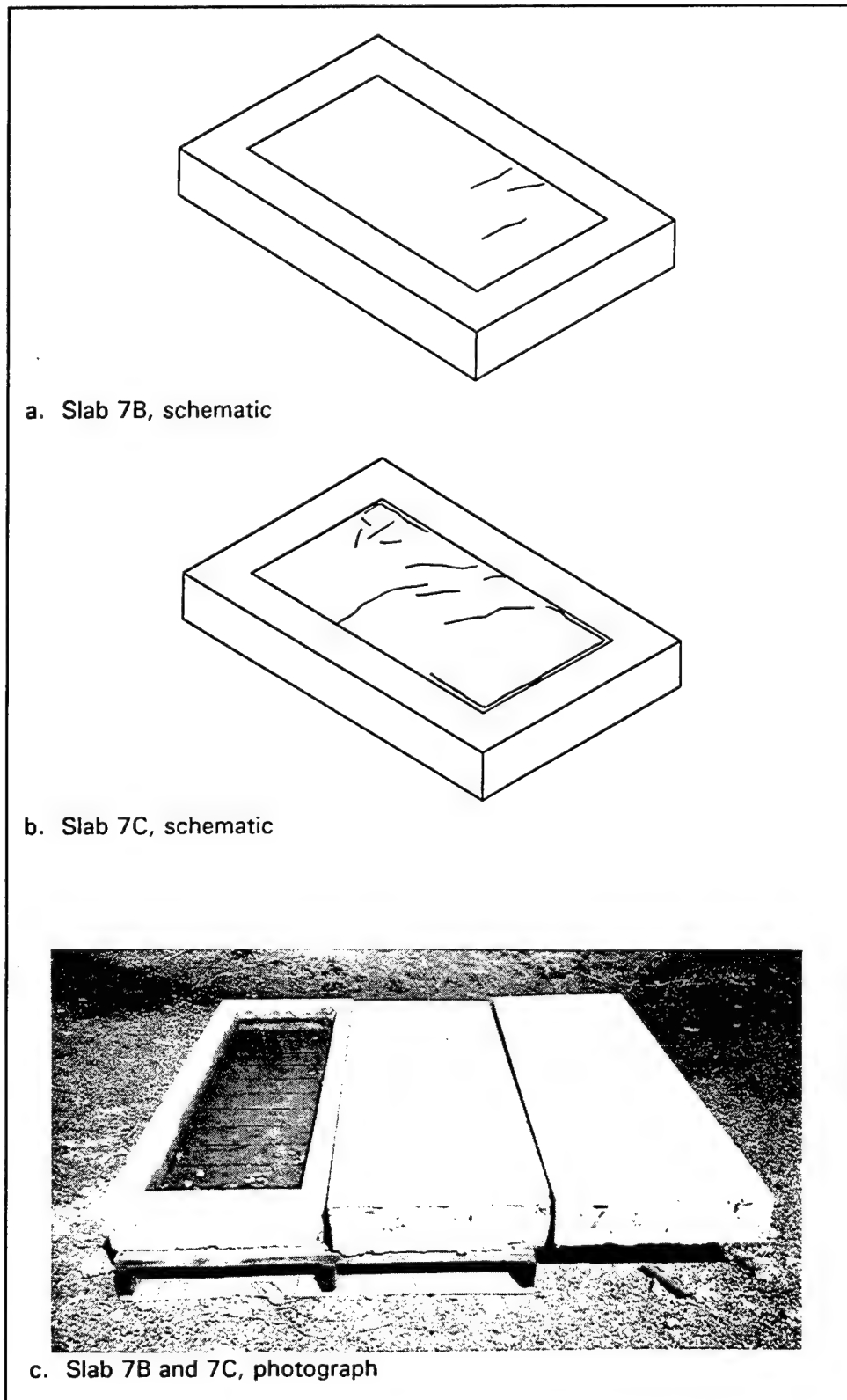
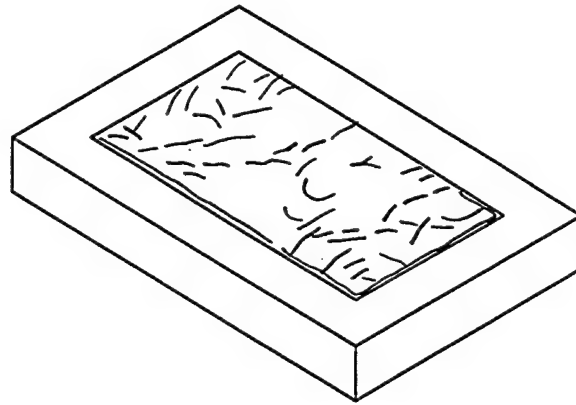
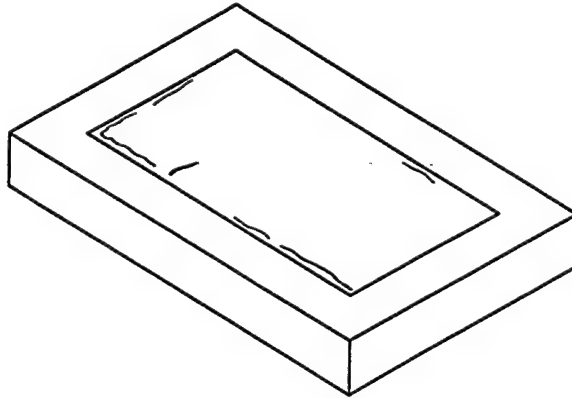


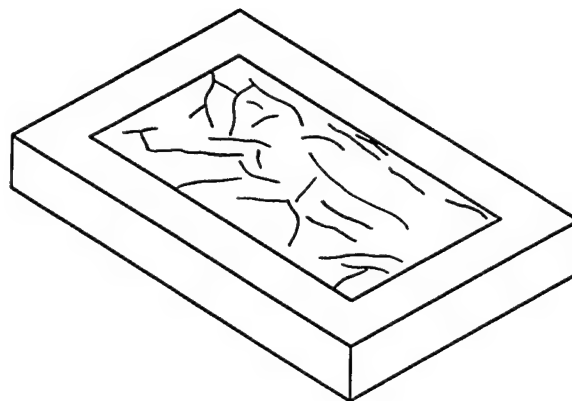
Figure 42. Cracking of Material No. 7 (Arizona)



a. Slab 10A



b. Slab 10B



c. Slab 10C

Figure 43. Cracking of Material No. 10 (Arizona)

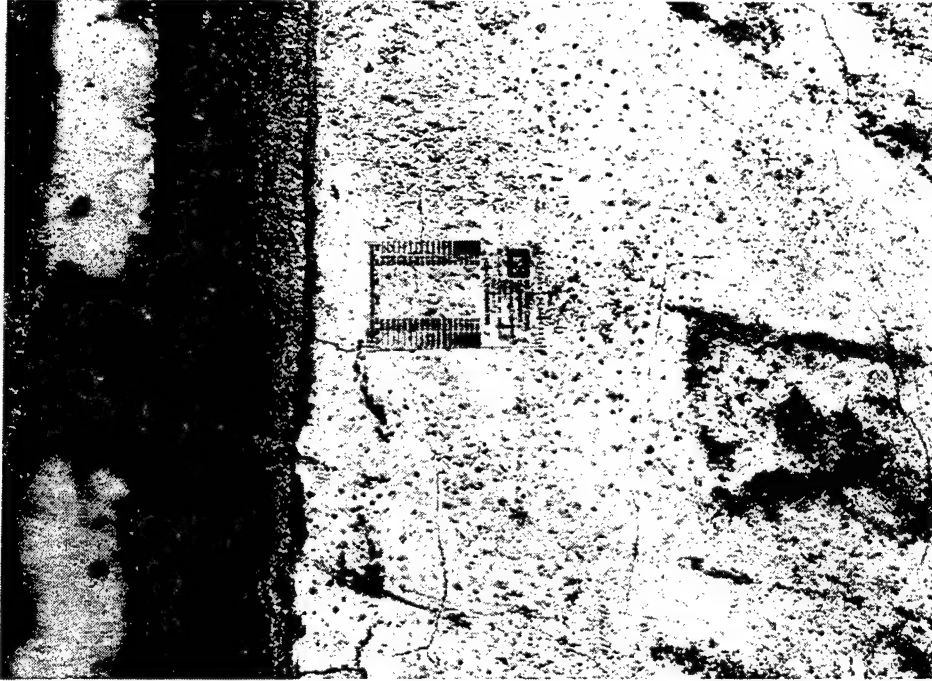


Figure 44. Cracking of Material No. 10C (Arizona)

Table 8
Summary of Results of Repair Monitoring

Material No.	Observations			Comments
	Florida	Illinois	Arizona	
1	No cracks.	No cracks.	No cracks.	Good resistance to cracking.
2	No cracks.	No cracks.	Edge cracking in all repairs.	Early age cracking when exposed to low humidity and high temperature.
3	No cracks.	No cracks.	Surface checking and one transverse crack.	Susceptible to cracking when exposed to low humidity and high temperature.
4	No cracks.	No cracks.	No cracks.	Good resistance to cracking.
5	Extensive severe cracking.	Surface crazing in all repairs and cracking in one repair.	Cracking in two repairs.	Prone to cracking, particularly when not extended with aggregate.
6	Cracking in one repair.	Fine surface cracking in two repairs.	Severe edge cracking in all repairs. One transverse crack.	Prone to cracking.
7	Very fine surface crazing.	Surface crazing.	Surface checking and cracking in all repairs.	Prone to surface crazing and checking. Cracked when exposed to low humidity and high temperature.
8	Fine surface crazing in each repair.	No cracks.	No cracks.	Good resistance to cracking. Surface crazing attributed to finishing.
9	Minor surface crazing in one repair.	No cracks.	No cracks.	Good resistance to cracking.
10	Very fine surface crazing and slab wall cracking in all repairs.	Pattern cracking in all repairs.	Severe cracking in all repairs.	Prone to surface crazing and cracking.
11	No cracks.	No cracks.	No cracks.	Good resistance to cracking.
12	No cracks.	Surface deterioration in one repair.	No cracks.	Good resistance to cracking.

Table 9
Relative Ranking of Materials Based on Repair Monitoring

Relative Rank	Summary of Cracking Behavior	Material No.
1-3	No cracks.	1
1-3	No cracks.	4
1-3	No cracks.	11
4	Surface deterioration of one repair in Illinois.	12
5-6	Fine surface crazing of each repair in Florida.	8
5-6	Minor surface crazing of one repair in Florida.	9
7-8	Surface checking and one transverse crack in Arizona.	3
7-8	Edge cracks in each repair in Arizona.	2
9-12	Minor surface crazing in Florida and Illinois, cracking in Arizona.	7
9-12	Surface cracking at all sites ranging from very fine to severe.	10
9-12	Cracked at each test site.	6
9-12	Cracked at each test site.	5

Overall, the 12 repair materials exhibited more resistance to cracking than was originally anticipated. Fine surface crazing of Material No. 8 in Florida, minor surface crazing of Material No. 9 in one repair in Florida, and minor surface deterioration of Material No. 12 in one repair in Illinois appear to be unrelated to dimensional compatibility properties. Therefore, results of these tests indicate six materials (Nos. 1, 4, 8, 9, 11, and 12) demonstrated satisfactory dimensional compatibility and resistance to cracking under the range of service conditions studied. In addition, two materials (Nos. 2 and 3) did not crack when exposed in Florida and Illinois, but did exhibit cracking when exposed to the high-temperature, low-humidity service environment in Arizona. The remaining materials (Nos. 5, 6, 7, and 10) cracked in each of the service environments.

No clear performance trends were found in comparisons of material performance in Florida and Illinois. However, the materials were much more sensitive to cracking under the hot and dry climate in Arizona.

Although material performance may be expected to vary between sites because of climatic conditions, material mixing and placing operations would not be expected to vary between sites because of the prescribed procedures and quality control, although some variation could be expected because of differences in crew and workmanship. Furthermore, the questionable cleanliness of the aggregates used in Illinois influenced the water demand of the materials and their workability. In contrast, the aggregates used in Florida and Arizona were cleaner, and these problems were eliminated. These are just a few of the many variables in application of the repair materials that make an exact analysis of the performance data difficult. However, these variables are typical of in situ repair applications. Consequently, it is believed that materials that demonstrated good overall performance in this field-testing program, in

otherwise equal conditions, will have a much higher probability of success in actual repairs compared with those materials that performed poorly.

Restrained Shrinkage Tests

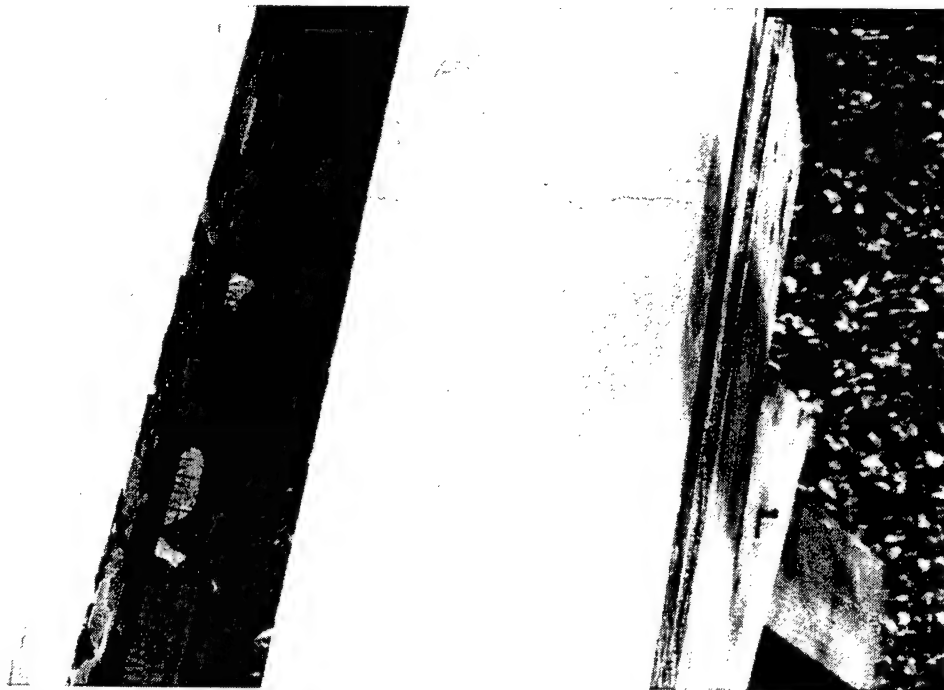
SPS Plate Test

As previously shown in Figure 18, the SPS Plate Test specimen is a beam that is fixed at one end and free to move at the other end. As the material expands or contracts in response to moisture and temperature changes, the free end deflects accordingly. The initial deflection measurements were made after completion of curing, and subsequent measurements were made periodically during the monitoring period. Detailed results of the SPS Plate Test are presented in Appendix B and summarized in Table 10.

Maximum deflections ranged from 2.03 mm (0.08 in.) to 16.5 mm (0.65 in.) with an overall average of 5.84 mm (0.23 in.) for tests conducted in Florida. Material No. 6 exhibited the largest deflection, which was approximately three times higher than the average. Generally, the maximum deflections measured in the Illinois tests were smaller compared with results of the Florida tests. Overall, the average maximum deflection in the Illinois tests was 3.56 mm (0.14 in.). Material No. 7 exhibited the largest deflection, which was approximately two times higher than the average. The maximum deflections measured in the Arizona tests were generally higher compared with results of tests at the other two sites. Overall, the average maximum deflection in the Arizona tests was 7.62 mm (0.30 in.). Material No. 7 again exhibited the largest deflection, which was approximately two times higher than the average. This maximum deflection was measured at 240 days age, just prior to the specimen cracking at 260 days (Figure 45).

Table 10
Summary of SPS Plate Test Results

Material No.	Maximum Deflection, mm (in.)		
	Florida	Illinois	Arizona
1	6.10 (0.24)	2.03 (0.08)	6.60 (0.26)
2	3.05 (0.12)	4.06 (0.16)	6.60 (0.26)
3	2.03 (0.08)	2.03 (0.08)	10.92 (0.43)
4	4.57 (0.18)	2.03 (0.08)	5.33 (0.21)
5	3.30 (0.13)	2.03 (0.08)	3.05 (0.12)
6	16.50 (0.65)	3.05 (0.12)	11.68 (0.46)
7	8.13 (0.32)	6.60 (0.26)	13.72 (0.54)
8	4.57 (0.18)	3.05 (0.12)	5.08 (0.20)
9	4.32 (0.17)	2.79 (0.11)	8.64 (0.34)
10	4.06 (0.16)	6.10 (0.26)	9.91 (0.39)
11	6.10 (0.24)	3.30 (0.13)	5.59 (0.22)
12	8.13 (0.32)	3.81 (0.15)	5.08 (0.20)



a. Top view



b. Side view

Figure 45. Material No. 7 cracked at 0.46 m (18 in.) from the fixed end (Arizona)

The repair materials were ranked based on their performance in the SPS Plate Test with results as shown in Table 11.

Table 11 Relative Ranking of Materials Based on SPS Plate Test Results		
Relative Rank	Maximum Deflection, mm (in.)	Material No.
1	3.30 (0.13)	5
2	5.08 (0.20)	8
3	5.33 (0.21)	4
4	6.10 (0.24)	11
5-6	6.60 (0.26)	1
5-6	6.60 (0.26)	2
7	8.13 (0.32)	12
8	8.64 (0.34)	9
9	9.91 (0.39)	10
10	10.92 (0.43)	3
11	13.72 (0.54)	7
12	16.50 (0.65)	6

German Angle Test

The German Angle Test was conducted to evaluate its potential for determining the cracking resistance of repair materials. The results of tests at each site are presented in Tables 12-14 and summarized in Table 15. The relative ranking of the various materials is shown in Table 16.

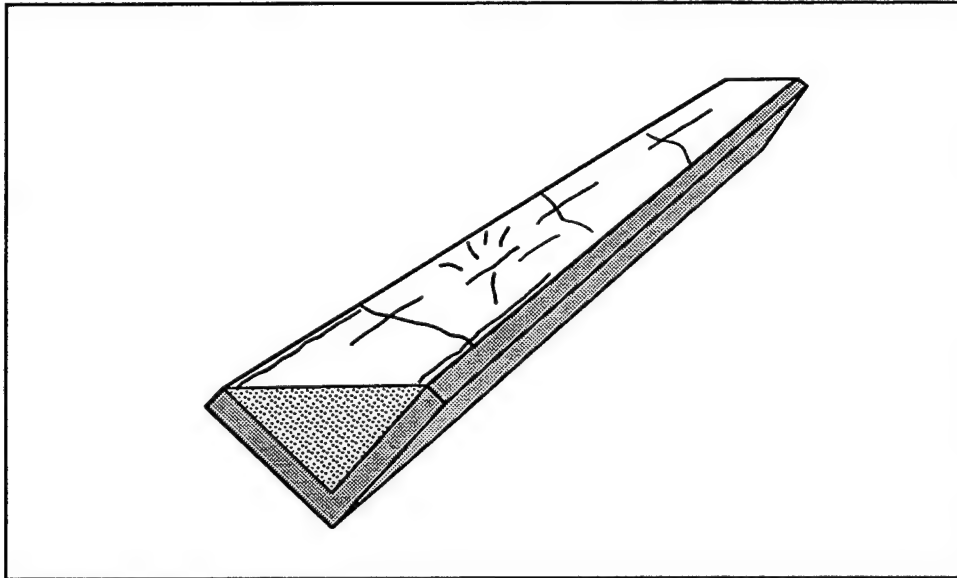
Five of the twelve repair materials cracked in the German Angle Tests conducted in Florida. Material Nos. 5 and 6 exhibited the most extensive cracking (Figures 46 and 47). These same two materials were the only ones exhibiting any distress in similar tests at the Illinois site. Seven of the twelve materials exhibited some degree of cracking in tests at the Arizona site. At least one crack was observed in each of the seven materials during the initial inspection at 7 days age. Six of the materials exhibited additional cracks in subsequent inspections. Material No. 7, in particular, exhibited continuing cracking up to 240 days age. This material also exhibited the highest deflection in the SPS Plate Test prior to failure of the specimen at 260 days.

Table 12
Results of German Angle Tests - Florida

Material No.	Date of Placement	Observation
1	08/04/94	No cracks.
2	08/02/94	No cracks.
3	08/02/94	Debonding cracks along the edges, and minor cracks from the edge toward the center.
4	08/03/94	No cracks.
5	08/01/94	Fine cracks and edge debonding cracking noted in first inspection (7 days age); two additional cracks at 28 days; large crack at 440 days. Figure 46.
6	08/02/94	Longitudinal cracks and two transverse cracks noted in first inspection (7 days age); one additional crack at 170 days; two additional cracks at 380 days. Figure 47.
7	08/04/94	Minor surface crazing noted at 14 days. Figure 48.
8	08/01/94	No cracks.
9	08/05/94	No cracks.
10	08/05/94	No cracks.
11	08/04/94	Minor surface crazing noted at 7 days. Figure 49.
12	08/05/94	No cracks.

Table 13
Results of German Angle Tests - Illinois

Material No.	Date of Placement	Observation
1	09/15/94	No cracks.
2	09/14/94	No cracks.
3	09/13/94	No cracks.
4	09/14/94	No cracks.
5	09/14/94	Material completely debonded from the angle at 135 days. Figure 50.
6	09/13/94	Eight transverse cracks noted at 14 days. Figure 51.
7	09/13/94	No cracks.
8	09/13/94	No cracks.
9	09/15/94	No cracks.
10	09/14/94	No cracks.
11	09/12/94	No cracks.
12	09/14/94	No cracks.

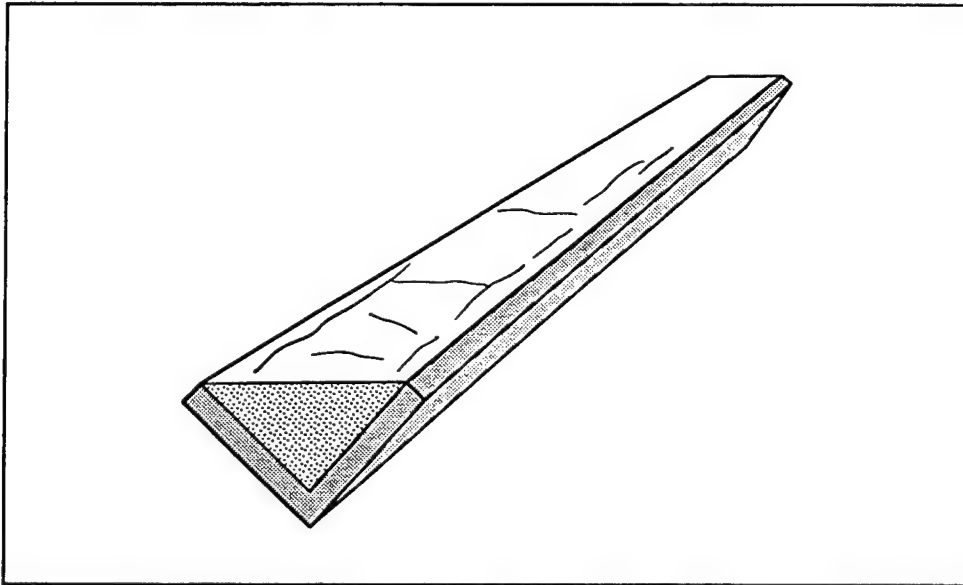


a. Schematic

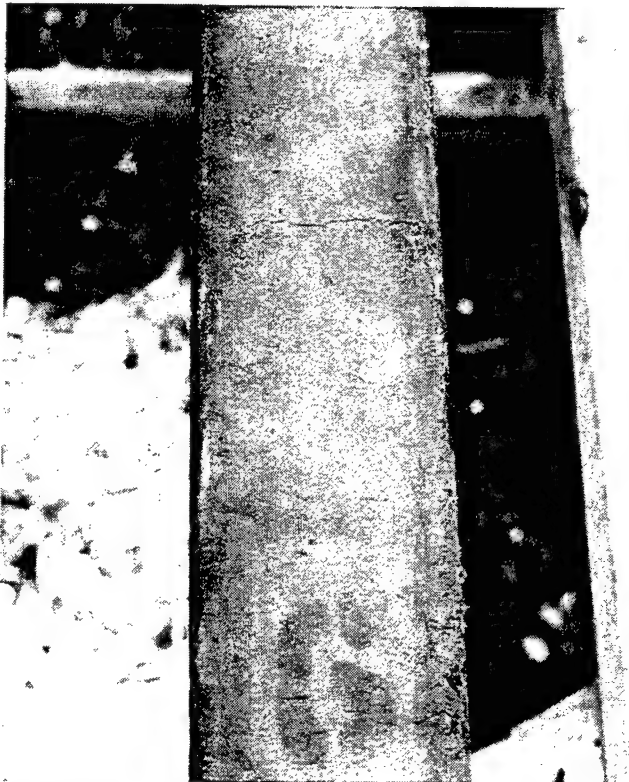


b. Photograph

Figure 46. Cracking of Material No. 5 (Florida)



a. Schematic



b. Photograph

Figure 47. Cracking of Material No. 6 (Florida)

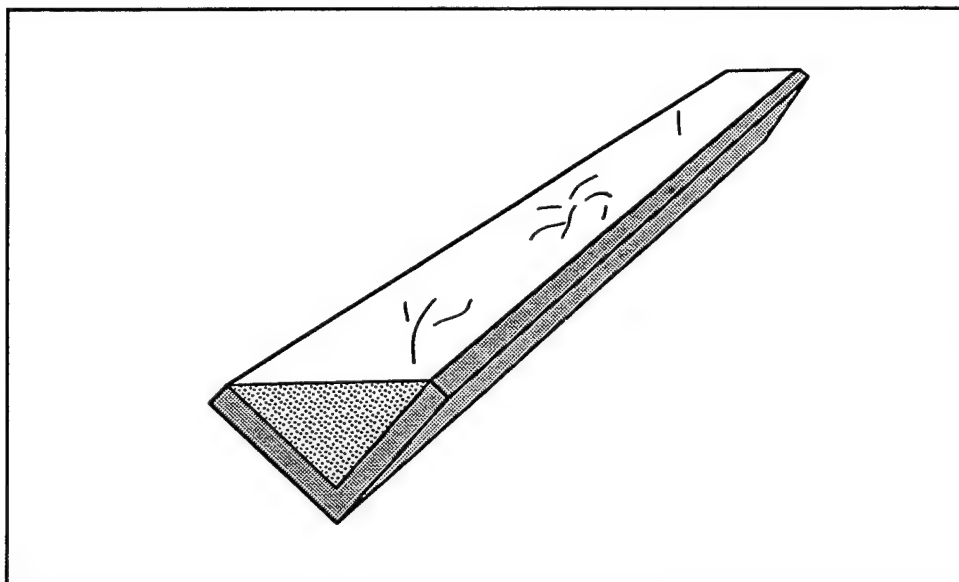


Figure 48. Cracking of Material No. 7 (Florida)

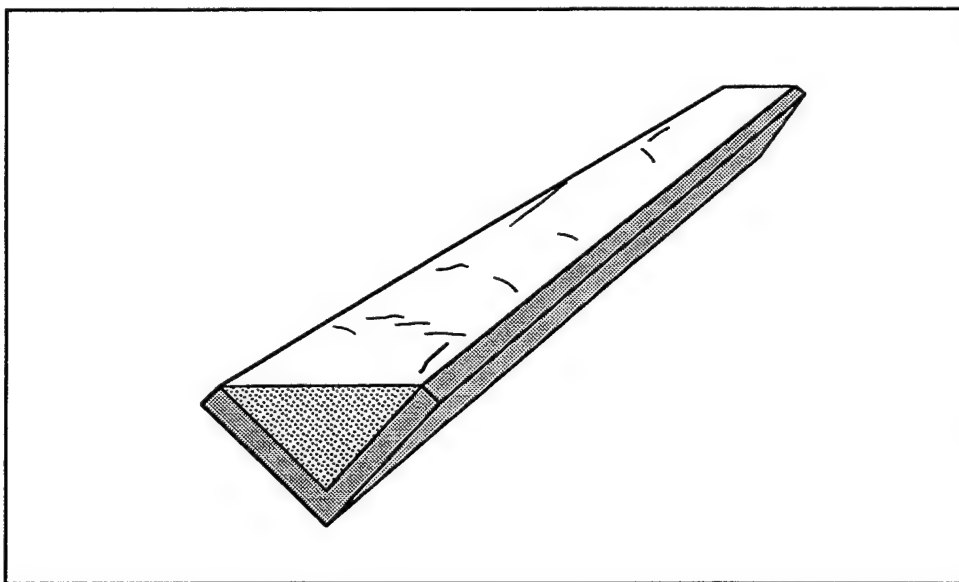


Figure 49. Cracking of Material No. 11 (Florida)

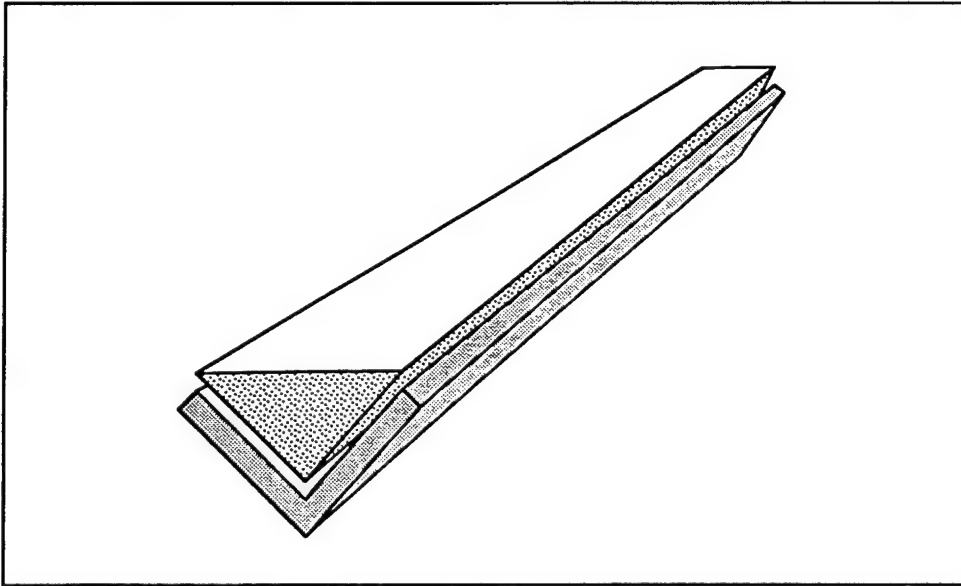
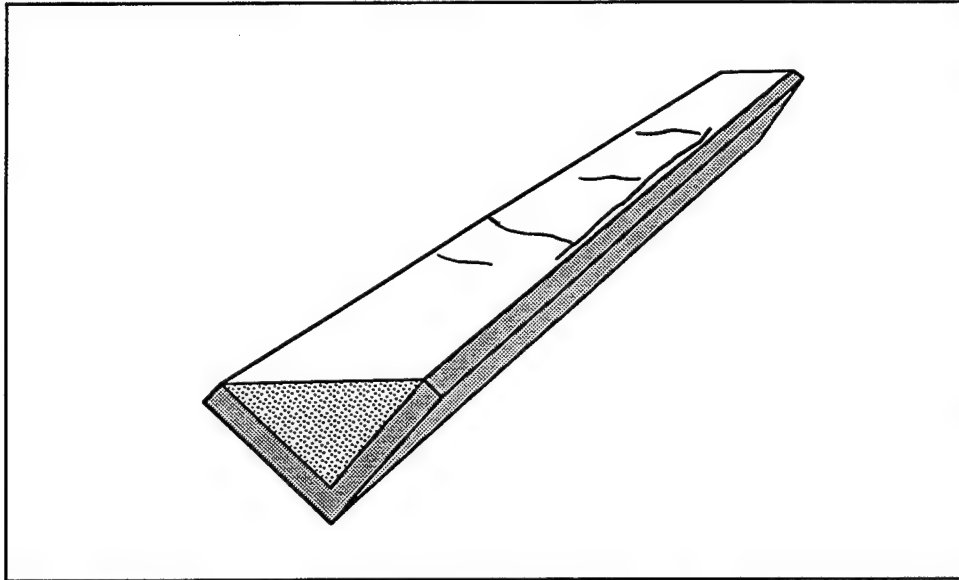
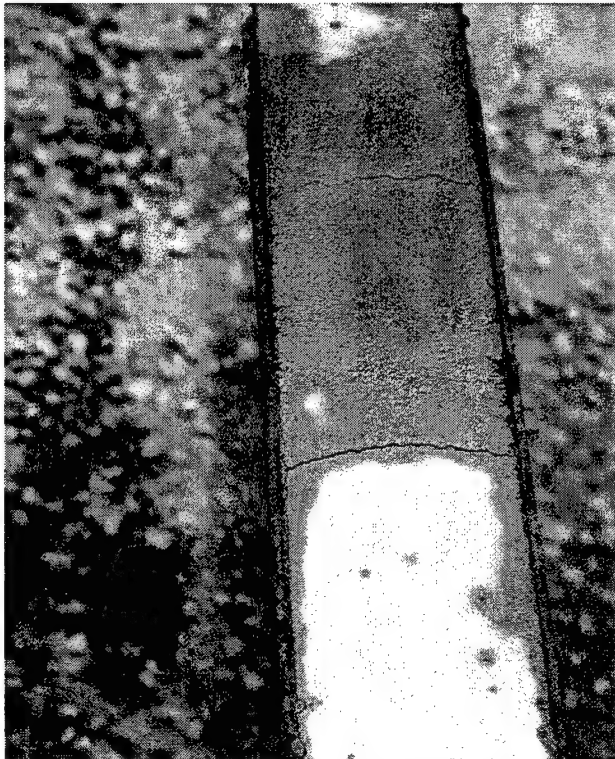


Figure 50. Debonding of Material No. 5 (Illinois)



a. Schematic



b. Photograph

Figure 51. Cracking of Material No. 6 (Illinois)

Table 14 Results of German Angle Field Tests - Arizona		
Material No.	Date of Placement	Observation
1	12/06/94	No cracks.
2	12/06/94	No cracks.
3	12/06/94	Three cracks noted at 7 days. Figure 52.
4	12/07/94	No cracks.
5	12/07/94	No cracks.
6	12/07/94	Two cracks noted at 7 days; three additional cracks at 21 days; one additional crack at 35 days. Figure 53.
7	12/07/94	Twelve cracks noted at 7 days; two additional cracks at 21 days; one additional crack at 28 days; two additional cracks at 35 days; one additional crack at 42 days; one additional crack at 170 days; four additional cracks at 200 days; one additional crack at 240 days. Figure 54.
8	12/08/94	Two cracks noted at 7 days; five additional cracks at 170 days. Figure 55.
9	12/08/94	One crack noted at 7 days; one additional crack at 35 days. Figure 56.
10	12/08/94	Thirteen cracks noted at 7 days; one additional crack at 35 days. Figure 57.
11	12/09/94	One crack noted at 7 days; one additional crack at 21 days; one additional crack at 200 days. Figure 58.
12	12/09/94	No cracks.

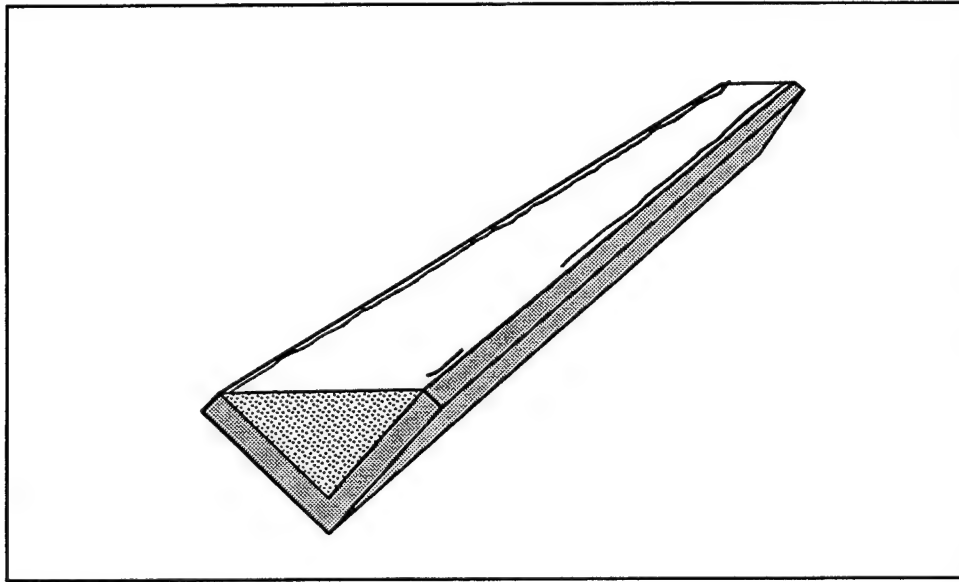


Figure 52. Cracking of Material No. 3 (Arizona)

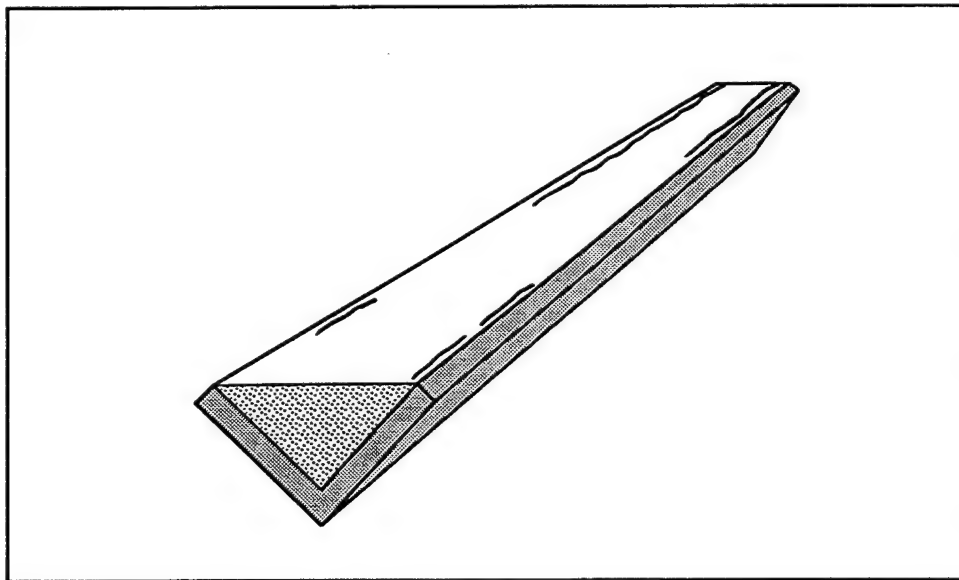
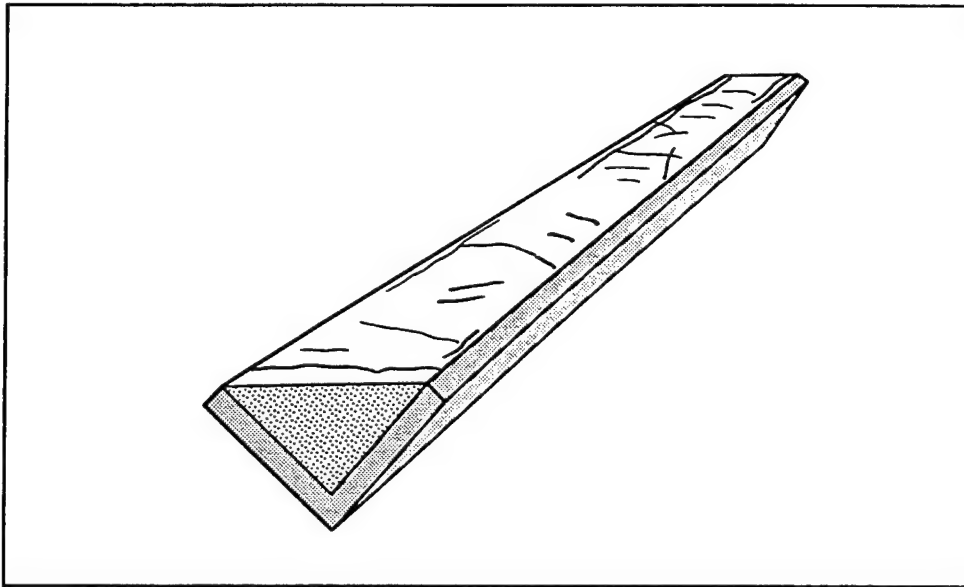


Figure 53. Cracking of Material No. 6 (Arizona)



a. Schematic



b. Photograph

Figure 54. Cracking of Material No. 7 (Arizona)

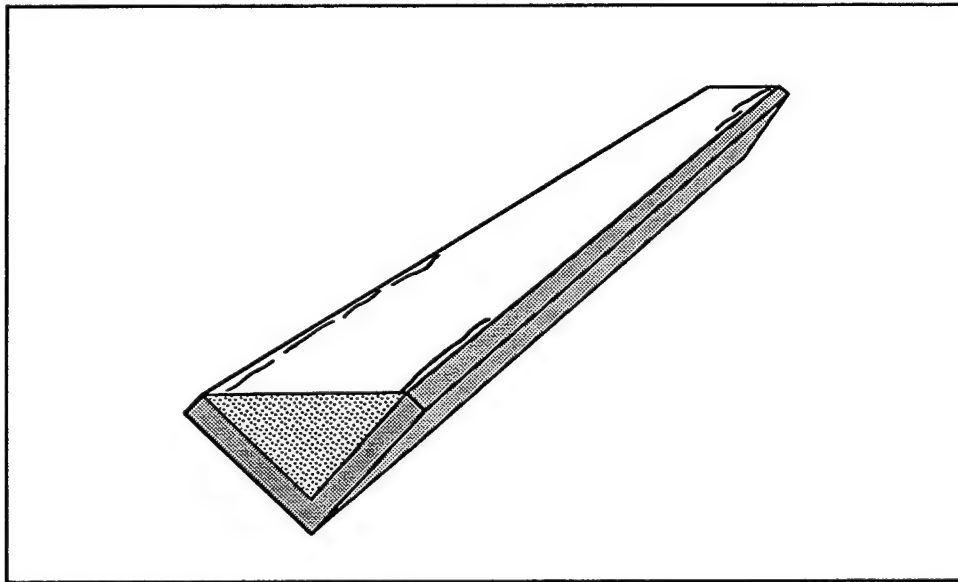


Figure 55. Cracking of Material No. 8 (Arizona)

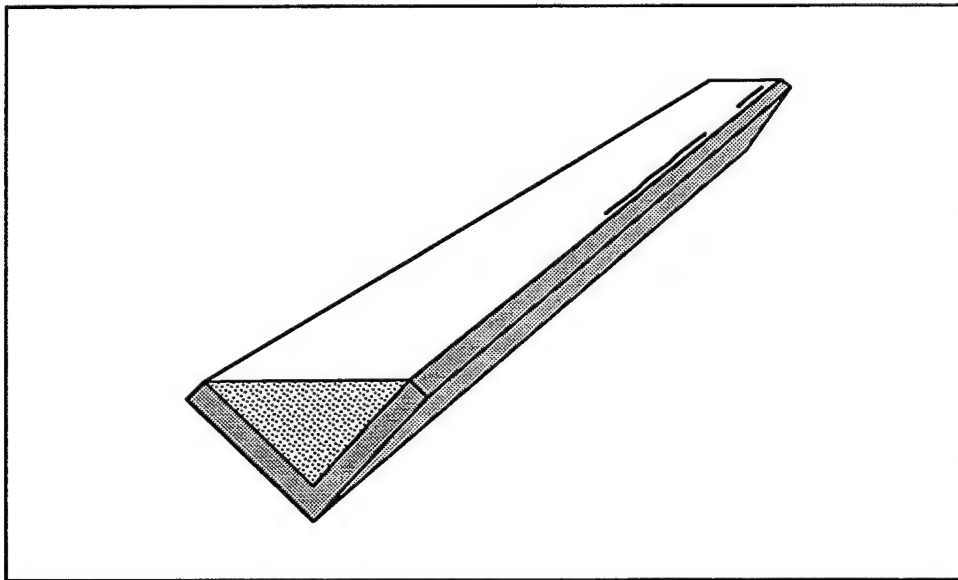


Figure 56. Cracking of Material No. 9 (Arizona)

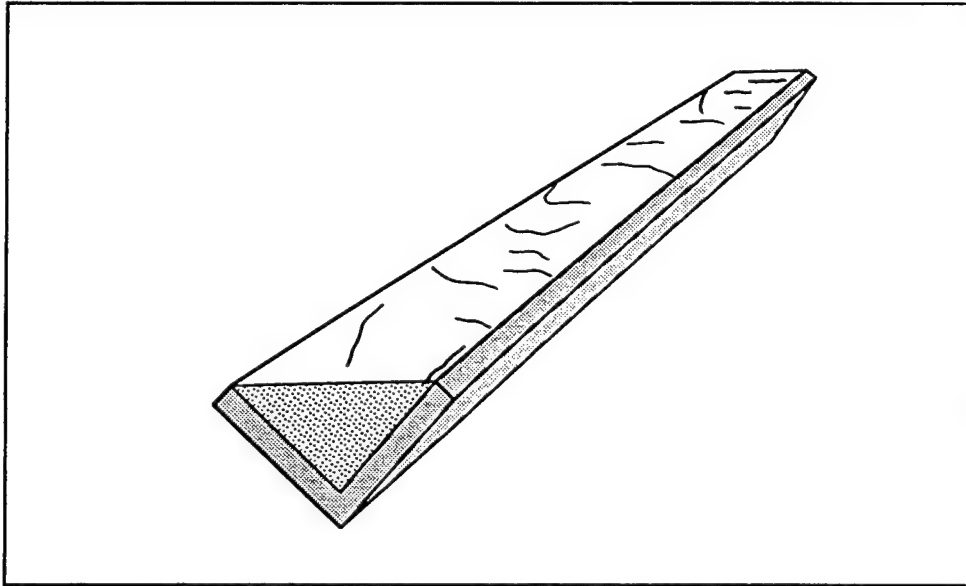


Figure 57. Cracking of Material No. 10 (Arizona)

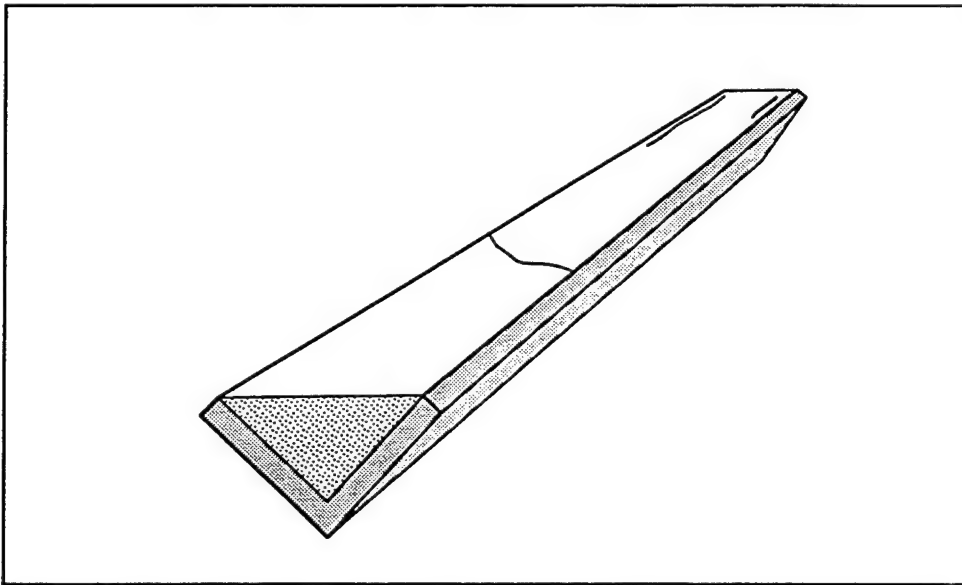


Figure 58. Cracking of Material No. 11 (Arizona)

Table 15
Summary of German Angle Test Results

Material No.	Observations		
	Test Locations		
	Florida	Illinois	Arizona
1	No cracks.	No cracks.	No cracks.
2	No cracks.	No cracks.	No cracks.
3	Debonded along the edges.	No cracks.	Cracked.
4	No cracks.	No cracks.	No cracks.
5	Cracked.	Completely debonded from the angle.	No cracks.
6	Cracked.	Cracked.	Extensive cracks.
7	Minor surface crazing.	No cracks.	Extensive cracks.
8	No cracks.	No cracks.	Cracked.
9	No cracks.	No cracks.	Cracked.
10	No cracks.	No cracks.	Extensive cracks.
11	Minor surface crazing.	No cracks.	Cracked.
12	No cracks.	No cracks.	No cracks.

Table 16
Relative Ranking of Materials Based on German Angle Test Results

Relative Rank	Summary of Cracking Behavior	Material No.
1-4	No cracks.	1
1-4	No cracks.	2
1-4	No cracks.	4
1-4	No cracks.	12
5-7	Cracked in Arizona.	8
5-7	Cracked in Arizona.	9
5-7	Cracked in Arizona.	11
8	Cracked in Arizona.	10
9	Minor surface crazing in Florida and Illinois; extensive cracking in Arizona.	7
10	Debonded in Florida; cracked in Arizona.	3
11	Cracked in Florida (not expanded with aggregate); debonded in Illinois.	5
12	Cracked at each site.	6

4 Summary and Conclusions

It is generally acknowledged that cracking of repair materials is the primary problem in the field of concrete repair. These cracks are typically the result of dimensional incompatibility between the repair material and the concrete substrate. Consequently, a comprehensive research program was initiated to develop performance criteria for the selection and specification of dimensionally compatible cementitious repair materials that will provide durable crack-free repairs. This report describes the field-testing phase of the overall study.

Twelve commercially available repair materials were selected for the study. The repair materials were chosen to represent a wide range in composition and properties, particularly drying shrinkage. Many of the material data sheets examined during the material selection process did not present objective technical data necessary to make informed selections of appropriate materials. General terms such as "low shrinkage" and "nonshrink" have little meaning without supporting data determined in accordance with specific standardized tests. A standard protocol for repair material data sheets should be developed and adopted by the concrete repair industry.

The field-testing program included installation of the selected materials in prefabricated repair cavities at each of three test sites and monitoring their performance during exposure to the varied service conditions. In addition, the field performance of each material was evaluated with two restrained drying shrinkage test methods. Results of the field tests will be correlated with results of the laboratory-testing phase of the overall study to develop performance criteria for dimensionally compatible repair materials.

Overall, the 12 repair materials exhibited more resistance to cracking than was originally anticipated. The selected repair geometry, while representative of many repairs, may not have been severe enough to ensure extensive cracking. However, the occurrence of less cracking than is usually observed in repair projects is more likely attributed to the workmanship and quality control exercised in this testing project.

An overall summary of the results of the field tests is shown in Table 17, and the relative ranking of the various materials is presented in Table 18. Resistance to cracking was the predominate factor in development of these rankings. It should be noted that these relative rankings do not reflect the

Table 17 Overall Summary of Field Test Results				
Material No.	SPS Test Maximum Deflection, mm (in.)	German Angle Observations	Repair Monitoring Observations	Conclusions
1	6.60 (0.26)	No cracks.	No cracks.	Good crack resistance.
2	6.60 (0.26)	No cracks.	Cracked in Arizona.	Early age cracking when exposed to low humidity and high temperature.
3	10.92 (0.43)	Cracked in Arizona.	Minor cracking in Arizona.	Susceptible to cracking when exposed to low humidity and high temperature.
4	5.33 (0.21)	No cracks.	No cracks.	Good crack resistance.
5	3.30 (0.13)	Cracked in Florida; debonded in Illinois.	Cracked.	Prone to cracking, particularly when not extended with aggregate.
6	16.50 (0.65)	Cracked.	Cracked.	Prone to cracking.
7	13.72(0.54)	Cracked severely in Arizona.	Surface crazing in Florida and Illinois. Cracked in Arizona.	Prone to surface crazing. Cracked when exposed to low humidity and high temperature.
8	5.08 (0.20)	Cracked in Arizona.	Fine surface crazing in Florida.	Good crack resistance. Surface crazing attributed to finishing.
9	8.64 (0.34)	Cracked in Arizona.	Minor surface crazing in one Florida repair.	Good crack resistance.
10	9.91 (0.39)	Cracked in Arizona.	Surface and edge cracking.	Prone to surface crazing and cracking.
11	6.10 (0.24)	Cracked in Arizona.	No cracks.	Good crack resistance.
12	8.13 (0.32)	No cracks.	Surface deterioration in one Illinois repair.	Good crack resistance.

Table 18 Relative Overall Ranking of Materials				
Overall Rank	SPS Plate Test	German Angle Test	Dimensional Stability (Cracking)	Material No.
1	3	1-4	1-3	4
2	4	5-7	1-3	11
3	5-6	1-4	1-3	1
4	7	1-4	4	12
5	2	5-7	5-6	8
6	8	5-7	5-6	9
7	5-6	1-4	8	2
8	10	10	7	3
9	9	8	9	10
10	11	9	10	7
11	1	11	12	5
12	12	12	11	6

magnitude of differences in performance between the repair materials and are not intended to promote or discredit any particular material. The rankings, along with material properties previously determined in laboratory tests, will be used in the next phase of the study to finalize performance criteria.

The following general conclusions are offered based on a comprehensive review and analysis of all information obtained in the field-test program:

- a. The various repair materials exhibited substantial differences in dimensional behavior and sensitivity to cracking. Only one-half of the materials tested (Nos. 4, 11, 1, 12, 8, and 9) demonstrated satisfactory performance irrespective of variations in service conditions within the ranges studied.
- b. Two materials (Nos. 2 and 3) were susceptible to cracking only when subjected to high-temperature and low-humidity conditions, and their performance is rated as marginal. The remaining four materials exhibited cracking in each exposure condition, and their performance is rated as unsatisfactory.
- c. Test results indicate that the SPS Plate Test can be used for a general assessment of a material's dimensional compatibility or resistance to cracking. The eight top-ranked materials exhibited maximum deflections ranging from 4.3 to 5.8 mm (0.17 to 0.23 in.) with an average of 5.1 mm (0.20 in.). With one exception, the remaining materials exhibited maximum deflections ranging from 6.9 to 10.4 mm (0.27 to 0.41 in.) with an average of 8.9 mm (0.35 in.), approximately 50-percent higher than the top-ranked materials. Only Material No. 5

with an average deflection of 2.8 mm (0.11 in.) exhibited poor crack resistance in the experimental repairs. This test method appears to be very sensitive to changes in temperature and humidity encountered in field tests; therefore, this method is currently recommended for cracking sensitivity tests only in controlled laboratory environments.

- d. Test results indicate that the German Angle Test can also be used for a general assessment of a material's resistance to cracking. Four materials did not crack in this test, and three of these materials were ranked Nos. 1, 3, and 4 in overall performance. The remaining material was ranked No. 7 overall with a marginal performance rating. The four materials with unsatisfactory performance ratings also exhibited cracks in the angle test and were ranked Nos. 8, 9, 11, and 12 in these tests.
- e. The high-early strength materials generally exhibited a rapid temperature rise following placement. This high heat of hydration, fast-setting characteristics, and rapid evaporation of surface moisture made finishing difficult and likely contributed to surface crazing observed in a number of repairs. These conditions also resulted in four cases of early age cracking involving two materials. These plastic-shrinkage cracks occurred despite immediate sprinkling of the repair surfaces with water after finishing. While the initiation of such cracking was not the result of dimensional incompatibility, subsequent cooling and restrained contraction of the repair material may have contributed to crack propagation. The critical importance of material workability and its impact on the timing and satisfactory accomplishment of finishing and curing operations was demonstrated throughout the testing program.
- f. In some cases, three repairs with the same material at a given test site would exhibit different behavior in resistance to cracking. These variations in performance are attributed, at least in part, to workmanship. Mixing and material placing operations would not be expected to vary between different repairs because of the detailed procedures and quality control. However, there is always the potential for human error in other areas such as weighing and batching. It is obvious from this study that the performance of a repair material often depends on such factors as mixture proportioning and construction operations, finishing and curing in particular. Proper application procedures are vital to satisfactory performance in a concrete repair; therefore, inspection and quality control warrants special attention.

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- a. ASTM C 39. "Standard test method for compressive strength of cylindrical concrete specimens."
- b. ASTM C 78. "Standard test method for flexural strength of concrete (using simple beam with third-point loading)."
- c. ASTM C 109. "Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or 50-mm cube specimens)."
- d. ASTM C 157. "Standard test method for length change of hardened hydraulic-cement mortar and concrete."
- e. ASTM C 190. "Standard test method for tensile strength of hydraulic cement mortars."
- f. ASTM C 191. "Standard test method for time of setting of hydraulic cement by Vicat needle."
- g. ASTM C 266. "Standard test method for time of setting of hydraulic-cement paste by Gillmore needles."
- h. ASTM C 348. "Standard test method for flexural of hydraulic cement mortars."
- i. ASTM C 469. "Standard test method for static modulus of elasticity and Poisson's Ratio of concrete in compression."

- j. ASTM C 496. "Standard test method for splitting tensile strength of cylindrical concrete specimens."
- k. ASTM C 596. "Standard test method for drying shrinkage of mortar containing portland cement."

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Appendix A Material Properties and Application Information for Repair Materials¹

¹ References cited in this appendix are listed in the References at the end of the main text.

Table A1 Material No. 1		
Composition	Recommended Use	
Cement mortar	Fast setting and high early strength mortar for highway and bridge deck patches, pavement joint repair, and highway structural repair	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Initial set, min: 75 °F - 16 95 °F - 15</p> <p>Compressive strength (ASTM C 109 (1994c)) at 24 hr: 75 °F - 48 MPa (7,000 psi) 95 °F - 41 MPa (5,900 psi)</p> <p>Flexural strength (ASTM C 78 (1994b)): 28 days - 5 MPa (700 psi)</p> <p>Drying shrinkage: ASTM C 157 Modified (1994d) by Alberta Transportation and Utilities (1987): 28 days - 0.022% 120 days - 0.032%</p>	<p><u>Mixing:</u> Mortar type mixer. For applications over 2-in. deep, should be extended by adding up to 50 lb of 3/8-in. pea gravel per 50-lb bag. Water - 5-1/2 pt. per 50-lb bag Mixing time: 3 min, minimum</p> <p><u>Application:</u> 15 min, maximum, for mixing, placing, and finishing. Work and tamp down the material firmly into the bottom and sides of the patch. Screed and trowel to the level of existing concrete.</p> <p><u>Curing:</u> In accordance with ACI 308 (1992).</p> <p><u>Hot-weather recommendations:</u> 1. Cool material and aggregate. 2. Cool mixing water. 3. Increase mix water addition by a maximum of 1-1/2 pt per bag.</p>	Very good workability.
<p>NOTE: To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F - 32)$. To obtain Kelvin (K) readings, use $K = (5/9) (F - 32) + 273.15$.</p>		

Table A2 Material No. 2		
Composition	Recommended Use	
Blend of portland cements, well-graded aggregates, and special additives. Ready-to-use material	High early strength concrete for repair of parking decks, concrete slabs, industrial flooring, masonry blockfill, highways, spalled concrete surfaces	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time: Initial - 6 hr Final - 8 hr</p> <p>Compressive strength (ASTM C 109 Modified (1994c)): 1 day - 20 MPa (3,000 psi) 7 days - 35 MPa (5,000 psi) 28 days - 48 MPa (7,000 psi)</p> <p>Drying shrinkage at 28 days: (ASTM C 157 Modified (1994d)) Data sheet - 0.04% Manufacturer's data - 0.048%</p> <p>Flexural strength (ASTM C 78 (1994b)): 28 days - 5 MPa (700 psi)</p> <p>Pot Life - 30 min</p>	<p><u>Mixing:</u> Mechanical mixer. Up to 4 qt of water per 80-lb bag. Mixing time: - 6 min, maximum.</p> <p><u>Application:</u> Place material quickly and continuously in full depth, working from one side of the repair area to the other, maintaining a minimum thickness of 1 in. Standard consolidation and finishing techniques.</p> <p><u>Curing:</u> Standard concrete curing practices are recommended.</p>	<p>Good workability, easily finished.</p>

Table A3
Material No. 3

Composition	Recommended Use	
A single component polymer-modified portland cement-based material. Contains acrylic polymer	High-strength material for horizontal surfaces. Can be placed from feather edge to 2 in. in one pass	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Compressive strength (ASTM C 109 (1994c)):</p> <p>1 day - 10 MPa (1,500 psi)</p> <p>7 days - 35 MPa (5,000 psi)</p> <p>14 days - 37 MPa (5,400 psi)</p> <p>28 days - 40 MPa (5,800 psi)</p> <p>Tensile strength (ASTM C 190 (ASTM 1994e))</p> <p>7 days - 4 MPa (570 psi)</p> <p>14 days - 4.1 MPa (600 psi)</p> <p>28 days - 4.5 MPa (650 psi)</p> <p>Drying shrinkage (ASTM C 157 Modified (1994d)):</p> <p>Manufacturer's data 0.05%</p>	<p><u>Mixing:</u> Mix 60-lb bag into 4-1/2 qt water with low-speed mixer. Up to 1 qt water can be added to adjust workability. Allow mix to "breathe" for 2-3 min, then remix for 1 min. For applications over 2 in. thick, 30 lb of 3/8-in. pea gravel should be added per 60-lb bag.</p> <p><u>Application:</u> Rough trowel area and allow to set to thumbprint. Finish smooth using a sweet coat after patch firms. Finish by troweling smooth. Do not overwork.</p> <p><u>Curing:</u> Wet cure for 3 days (based on manufacturer's recommendation; no mist curing required is stated in material data sheet).</p> <p>Material was preblended with pea stone and supplied in 80-lb bags.</p> <p>Manufacturer recommended 3-1/2 qt water per 80-lb bag.</p>	Easily finished.

Table A4 Material No. 4		
Composition	Recommended Use	
Cement-based concrete	High early strength material for horizontal and vertical use	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time (ASTM C 191 (ASTM 1994f)): Initial - 25 min Final - 35 min</p> <p>Compressive strength: (ASTM C 109 Modified (1994c)): 3 hr - 28 MPa (4,000 psi) 1 day - 35 MPa (5,000 psi) 7 days - 52 MPa (7,500 psi) 28 days - 55 MPa (8,000 psi)</p> <p>Flexural strength (ASTM C 78 (1994b)): 7 days - 8 MPa (1,200 psi)</p> <p>Shrinkage (ASTM C 157 Modified (1994c)): Data sheet - 28 days - 0.00% Manufacturer's data - 28 days - 0.05%</p>	<p><u>Mixing:</u> Mortar mixer is recommended. For application over 2 in. deep, should be extended with 25 lb pea gravel. Water - from 2-1/2 to 3 qt per 50-lb bag Mixing time: from 2 to 5 min</p> <p><u>Application:</u> Provides about 20 min working time. Pour from one side of the cavity to the other side. Do not place in layers. Material can be troweled or poured into the area to be repaired. After leveling, the repair can be broomed, brushed, or troweled.</p> <p><u>Curing:</u> When surface hardens, soak the surface with sufficient water and keep wet for at least 30 min.</p>	<p>Good workability. Outgassing observed in IL and AZ tests.</p>

Table A5
Material No. 5

Composition	Recommended Use	
Concrete patching material	High-strength, rapid setting material for repair of bridge decks, concrete pavements, airport runways and taxiways, industrial floors, loading docks, general concrete, precast and prestressed concrete	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time (ASTM C 266 (1994g)): Initial - 15-20 min Final - 20-25 min</p> <p>Compressive strength (ASTM C 109 Modified (1994c)): 1 hr - 17-21 MPa (2,500-3,000 psi) 3 hr - 48-55 MPa (7,000-8,000 psi) 3 days - 62-29 MPa (9,000-10,000 psi)</p> <p>Drying shrinkage (ASTM C 157 (1994d)): 28 days - 0.041% Ultimate - 0.056% (Personal communication with Tony B. Husbands, WES, Vicksburg, MS, May 1994).</p>	<p><u>Mixing:</u> Mortar mixer. It was recommended initially not to use aggregate extension for the 3-in.-thick experimental repairs. Total mixing water per 50-lb bag not to exceed 1-1/2 gal. All required water shall be put in the mixer, and then material is to be added. Mixing time: 2-3 min</p> <p><u>Application:</u> Material should be placed in about 10 min. Place from one side to the other, working material into sides and bottom of patch area. Screed and level to proper elevation. Trowel with metal tools only.</p> <p><u>Curing:</u> As soon as possible without marring, begin curing with water. Saturated burlap may also be used. Maintain a wet surface for a minimum of 1 hr, then apply curing compound.</p>	<p>No aggregate included in FL test. Relatively quick set. Rapid loss of workability. High heat of hydration. Plastic shrinkage cracks. Material extended with 25 lb of pea gravel in IL and AZ tests. Prewetting the aggregate with part of the mixing water prolonged set time. Still had high heat of hydration.</p>

Table A6
Material No. 6

Composition	Recommended Use	
Polymer and microsilica modified cement-based repair material	High-strength repair material for parking decks, bridge structures, pier and dock supports, concrete in marine environment, sewage treatment plants, dams, and retaining walls. Material for horizontal and formed vertical and overhead surfaces	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time: 4-6 hr</p> <p>Compressive strength (ASTM C 109 (1994c)):</p> <p>1 day - 17 MPa (2,500 psi)</p> <p>3 days - 32 MPa (4,700 psi)</p> <p>7 days - 41 MPa (6,000 psi)</p> <p>28 days - 63 MPa (9,200 psi)</p> <p>Flexural strength (ASTM C 348 (1994h)):</p> <p>1 day - 4 MPa (600 psi)</p> <p>7 days - 9 MPa (1,270 psi)</p> <p>28 days - 11 MPa (1,500 psi)</p> <p>Tensile strength (ASTM C 496 (1994j)):</p> <p>7 days - 3.7 MPa (535 psi)</p> <p>28 days - 5.7 MPa (820 psi)</p> <p>Drying shrinkage (ASTM C 157 Modified (1994d)):</p> <p>28 days - 0.086%</p> <p>Modulus of elasticity:</p> <p>28 days - 42.3 GPa (6.14 x 10⁶ psi)</p>	<p><u>Mixing:</u> Mortar mixer. No aggregate extension is recommended.</p> <p>Mixing water per 50-lb bag - 0.53 to 0.58 gal. Add water in mixer and slowly add material while mixing.</p> <p>Mixing time: - 5 min, minimum</p> <p><u>Application:</u> No specific recommendations in the data sheet. Should be handled as regular concrete (Personal communication with Duane Emmett, The Euclid Chemical Co., Cleveland, OH, April 1994).</p> <p>Working time: about 45 min at (73 °F); 20 min at 90 °F.</p>	<p>Marginal workability. Very short time for finishing. Plastic shrinkage cracks in one FL repair.</p>

Table A7
Material No. 7

Composition	Recommended Use	
A single component, polymer-modified repair mortar	Repair of horizontal, vertical, and overhead concrete surfaces	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time: Initial - 20 to 30 min</p> <p>Compressive strength (ASTM C 109 (1994c)): 1 day - 20 MPa (2,960 psi) 7 days - 47 MPa (6,825 psi) 14 days - 48 MPa (6,915 psi) 28 days - 49 MPa (7,050 psi)</p> <p>Flexural strength (ASTM C 348 (1994h)): 7 days - 5.8 MPa (845 psi) 28 days - 6.4 MPa (930 psi)</p> <p>Tensile strength (ASTM C 190 (1994e)): 1 day - 1.9 MPa (270 psi) 7 days - 3.3 MPa (475 psi) 14 days - 4.1 MPa (600 psi) 28 days - 4.1 MPa (600 psi)</p> <p>Drying shrinkage: (ASTM C 157 Modified (1994d)): Ultimate - 0.07%</p>	<p><u>Mixing:</u> Material is to be extended with 25 lb of pea stone per 50-lb bag. Mixing water: 4-5 qt per bag (data sheet). Manufacturer's recommendation - 5-3/4 qt per bag. Mix to a no lump, putty-like consistency.</p> <p><u>Application:</u> Trowel the mix into patch cavity with firm pressure. Overbuild patch by at least 1/4 in. Depending on the temperature and humidity, the material will take an initial set in about 30 min. After the initial set, the material can be shaved for 1 to 2 hr to achieve the desired shape. The material may be floated, wet-brushed, or troweled smooth to finish.</p> <p><u>Curing:</u> Curing is not needed except in very hot, dry weather.</p>	<p>Very fast set. Very difficult to finish when recommended amount of water was used, even with ambient temperature of 60 to 75 °F. Increasing water content and cooling with ice was necessary to obtain sufficient time for finishing.</p>

Table A8
Material No. 8

Composition	Recommended Use	
A single component, lightweight, fiber and polymer-modified repair material	For vertical and overhead high building applications	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Compressive strength: (ASTM C 109 (1994c)): 7 days - 28-38 MPa (4,000-4,800 psi) 28 days - 34.5-40 MPa (5,000-5,800 psi)</p> <p>Flexural strength (ASTM C 348 (1994h)): 7 days - 5 MPa (725 psi)</p> <p>Tensile strength (ASTM C 190 (1994c)): 7 days - 2 MPa (290 psi)</p> <p>Drying shrinkage (ASTM C 157 Modified (1994d)): 28 days - 0.04-0.06%</p> <p>Drying shrinkage (Coutinho Ring): 7 days - no cracks 28 days - no cracks</p>	<p><u>Mixing:</u> A force action mixer is recommended. Mixing water: 6.5 pt per 45-lb bag. Dependent on the ambient temperature and the desired consistency, additional water may be added up to 7 pt per 45-lb bag. Mixing time: 3-5 min. Pot Life: about 30 min</p> <p><u>Application:</u> Material is applied by hand or trowel. The repair is finished by striking off with a straight edge and closing with a steel float.</p> <p><u>Curing:</u> Should be cured immediately after finishing in accordance with good concrete practice (ACI 308) (ACI 1992).</p>	<p>Very difficult to place, even with additional water. Internal vibration was inadequate. After tamping, mixture was easily finished.</p>

Table A9
Material No. 9 (Control)

Composition	Recommended Use	
Portland cement concrete	For bridge overlays	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Compressive strength: 28 days -28 MPa (4,000 psi)</p> <p>This "control" concrete mix was produced and packaged by American Stone Mix, Inc., on investigator's request; therefore, manufacturer's technical data do not exist.</p> <p>Drying shrinkage data, 0.06% at 28 days, were selected based on standard data for concrete of average quality.</p>	<p><u>Mixing:</u> Mechanical mixer. Mix 80-lb bag with up to 4 qt of water. Mixing time: 6 min, maximum Concrete is ready to use and does not require addition of aggregate.</p> <p><u>Application:</u> Concrete should be placed in prepared area in full depth, working from one side of the repair area to the other. Concrete shall be properly compacted without voids. Finishing and curing of this material are no different from good practices of conventional concrete technology.</p> <p><u>Curing:</u> Should be cured immediately after finishing in accordance with good concrete practice (ACI 308 (ACI 1992)).</p>	<p>Good workability.</p>

Table A10
Material No. 10

Composition	Recommended Use	
One-component polymer-modified cement-based mortar	Fast-setting repair material for horizontal and formed vertical applications in interior and exterior environments	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Set time: Initial - 1.5 hr Final - 2 hr</p> <p>Compressive strength: (ASTM C 109 (1994c)): 1 day - 17 MPa (2,500 psi) 7 days - 38 MPa (5,500 psi) 28 days - 52 MPa (7,500 psi)</p> <p>Flexural strength (ASTM C 348 (1994h)): 28 days - 10 MPa (1,500 psi)</p> <p>Tensile strength (ASTM C 496 (1994j)): 1 day - 2.6 MPa (375 psi) 7 days - 3.1 MPa (450 psi) 28 days - 4 MPa (600 psi)</p> <p>Drying shrinkage (ASTM C 596 (1994k)): 28 days - 0.093%</p> <p>Modulus of Elasticity (ASTM C 469 (1994i)): 28 days - 15.1 GPa (2.2×10^6 psi)</p>	<p><u>Mixing:</u> Mortar mixer is recommended. Mix 55-lb bag with 0.79 gal water. Mixing time: 3-5 min For applications more than 1 in. in thickness, an extension of 25 lb pea gravel, 3/8 in. per 55-lb bag is required. Working time: 30 min The material may be finished as any other conventional concrete mix.</p> <p><u>Curing:</u> Minimum curing time for wet curing - 2 days. Curing compound may be used. Manufacturer's recommended curing for this project: 2 days moist cure, and then apply curing compound.</p>	<p>Very dry after mixing, then becomes workable to the point of self-leveling. Very cohesive and sticky making it difficult to finish. Sensitive to timing of finishing operations.</p>

Table A11
Material No. 11

Composition	Recommended Use	
One-component cement-based repair mortar	Fast-setting and high early strength mortar for highway and bridge deck patches, pavement joint repair, and highway structural repair	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Working time: 30-40 min</p> <p>Compressive strength: (ASTM C-109 (1994c)): 1 day - 17 MPa (2,500 psi) 7 days - 41 MPa (600 psi) 28 days - 55 MPa (8,000 psi)</p> <p>Flexural strength (ASTM C 78 (1994b)): 28 days - 5.3 MPa (770 psi)</p> <p>Drying shrinkage (ASTM C 157 (1994d)): 28 days - 0.06%</p> <p>Modulus of Elasticity: 28 days - 33.1 GPa (4.8 x 10⁶ psi)</p>	<p><u>Mixing:</u> Mortar mixer is recommended. Mix 55-lb bag with 0.79 gal water. Water: Approximately 0.5 gal per 55-lb bag to obtain a slump of 4-6 in. Mixing Time: 3-5 min. No aggregate extension is required. No special requirements for finishing.</p> <p><u>Curing:</u> Moist cure for 2 days, then apply curing compound.</p>	<p>Good workability.</p>

Table A12
Material No. 12

Composition	Recommended Use	
Two-component, polymer-modified portland-cement mortar	For overlays, structural repairs for parking facilities, industrial plants, walkways, bridges, tunnels, and dams.	
Manufacturer's Technical Data	Manufacturer's Application Data	Field Observations
<p>Application time: about 15 min</p> <p>Finishing time: 20 to 60 min</p> <p>Compressive strength (ASTM C 39 (1994a)): 1 day - 14 MPa (2,000 psi) 3 days - 28 MPa (4,100 psi) 28 days - 42 MPa (6,100 psi)</p> <p>Flexural strength (ASTM C 78 (1994b)): 28 days - 8.3 MPa (1,200 psi)</p> <p>Tensile strength (ASTM C 496 (1994j)): 1 day - 2.8 MPa (400 psi) 7 days - 3.5 MPa (500 psi) 28 days - 5.5 MPa (800 psi)</p> <p>Drying shrinkage data for this material are not presented by the manufacturer. The shrinkage property of 0.147% as tested by Alberta Transportation and Utilities (1987) for a similar product was used.</p>	<p><u>Mixing:</u> Mortar mixer. Pour all component "A" into mixer, add all of component "B," then introduce aggregate 42 lb per unit; aggregate has to be SSD.</p> <p><u>Application:</u> Mix must be scrubbed into the substrate. Force material against the edge of the repair, working toward the center. After filling repair, consolidate, then screed. Allow to set to desired stiffness, then finish with wood or sponge float.</p> <p><u>Curing:</u> Moist curing recommended.</p>	<p>Good workability in AZ when ambient temperature was 67 °F. Difficult to place, consolidate, and finish in FL and IL, where ambient temperatures were above 85 °F.</p>

Appendix B

Field Data

Table B1
Monitoring Schedule for the Three Exposure Sites

		Evaluation Number																		
		Time ¹ , days																		
Test Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Florida	1	7	14	21	-	35	42	75	105	135	170	200	240	260	320	380	440	500	560	-
Illinois	1	7	14	21	28	35	42	75	105	135	170	200	240	260	320	380	440	500	560	-
Arizona	1	7	14	21	28	35	42	75	105	135	170	200	240	260	320	380	440	500	560	620
¹ Days after completion of curing.																				

Table B2

Results of SPS Plate Tests Conducted in Florida

Material Code	Average of Three Deflection Measurements																			Maxi- mum	Deflec- tion ² In. (mm)	
	Time, days																					
	1 ¹	7	14	21	28	35	42	75	105	135	170	200	240	260	320	380	440	500	560			620
1	2.32	2.27	2.32	2.32	2.32	2.32	2.32	2.32	2.35	2.34	2.34	2.36	2.35	2.36	2.38	2.38	2.39	2.41	2.43	-	2.43	0.24 (6.10)
2	2.23	2.23	2.24	2.24	2.24	2.23	2.24	2.24	2.31	2.31	2.29	2.26	2.29	2.28	2.30	2.29	2.30	2.31	2.30	-	2.31	0.12 (3.05)
3	2.17	2.15	2.17	2.17	2.17	2.17	2.17	2.17	2.30	2.18	2.26	2.27	2.26	2.26	2.25	2.26	2.26	2.27	2.27	-	2.27	0.08 (2.03)
4	2.29	2.28	2.31	2.3	2.31	2.3	2.29	2.3	2.37	2.35	2.33	2.31	2.22	2.23	2.25	2.29	2.32	2.32	2.33	-	2.37	0.18 (4.57)
5	2.22	2.25	2.27	2.26	2.27	2.26	2.26	2.27	2.32	2.3	2.29	2.3	2.25	2.25	2.26	2.26	2.25	2.26	2.25	-	2.32	0.13 (3.30)
6	2.69	2.65	2.72	2.74	2.76	2.76	2.75	2.76	2.84	2.82	2.73	2.71	2.58	2.46	2.33	2.32	2.3	2.31	2.32	-	2.484	0.65 (16.5)
7	2.27	2.27	2.34	2.36	2.28	2.29	2.35	2.31	2.51	2.49	2.51	2.49	2.46	2.48	2.49	2.43	2.49	2.51	2.5	-	2.51	0.32 (8.13)
8	2.28	2.29	2.29	2.32	2.29	2.30	2.32	2.29	2.35	2.30	2.36	2.33	2.34	2.35	2.34	2.33	2.35	2.36	2.37	-	2.37	0.18 (4.57)
9	2.22	2.24	2.28	2.35	2.35	2.30	2.34	2.30	2.36	2.34	2.31	2.32	2.31	2.31	2.31	2.24	2.23	2.25	2.25	-	2.36	0.17 (4.32)
10	2.23	2.23	2.23	2.22	2.22	2.23	2.22	2.22	2.24	2.26	2.26	2.24	2.25	2.26	2.25	2.28	2.29	2.34	2.35	-	2.235	0.16 (4.06)
11	2.38	2.38	2.39	2.39	2.37	2.38	2.39	2.38	2.43	2.40	2.40	2.41	2.39	2.40	2.39	2.38	2.37	2.38	2.39	-	2.43	0.24 (6.10)
12	2.43	2.44	2.45	2.45	2.45	2.44	2.45	2.45	2.51	2.49	2.47	2.49	2.46	2.39	2.42	2.43	2.45	2.42	2.49	-	2.51	0.32 (8.13)

¹ Initial reading.

² Dimension at zero deflection is 55.5 mm (2.19 in.).

¹ Initial reading.² Dimension at zero deflection is 55.5 mm (2.19 in.).

Table B3
Results of SPS Plate Tests Conducted in Illinois

Average of Three Deflection Measurements																					Maxi- mum	Deflec- tion ² In. (mm)	
Material Code	Time, days																						
	1 ¹	7	14	21	28	35	42	75	105	135	170	200	240	260	320	380	440	500	560	620			
1	2.25	2.27	2.27	2.26	-	2.25	2.27	2.26	2.25	2.26	2.27	2.26	2.24	2.25	2.26	2.26	2.25	2.25	2.25	2.27	-	2.27	0.08 (2.03)
2	2.28	2.28	2.31	2.31	-	2.31	2.32	2.31	2.30	2.32	2.32	2.31	2.32	2.34	2.35	2.34	2.33	2.32	2.35	-	2.35	0.16 (4.06)	
3	2.19	2.20	2.20	2.19	-	2.20	2.23	2.20	2.21	2.25	2.23	2.23	2.23	2.27	2.25	2.26	2.23	2.21	2.27	-	2.27	0.08 (2.03)	
4	2.24	2.24	2.25	2.25	-	2.25	2.25	2.25	2.26	2.25	2.26	2.25	2.26	2.27	2.27	2.27	2.27	2.26	2.27	-	2.27	0.08 (2.03)	
5	2.24	2.24	2.26	2.25	-	2.25	2.25	2.26	2.26	2.25	2.26	2.27	2.27	2.26	2.26	2.26	2.25	2.26	2.27	-	2.27	0.08 (2.03)	
6	2.26	2.26	2.27	2.27	-	2.26	2.28	2.27	2.26	2.26	2.26	2.27	2.26	2.28	2.28	2.29	2.29	2.3	2.31	-	2.31	0.12 (3.05)	
7	2.3	2.32	2.37	2.41	-	2.37	2.39	2.37	2.34	2.39	2.44	2.45	2.4	2.39	2.33	2.34	2.32	2.3	2.44	-	2.45	0.26 (6.60)	
8	2.23	2.23	2.24	2.24	-	2.24	2.26	2.25	2.24	2.24	2.24	2.25	2.25	2.31	2.29	2.30	2.26	2.24	2.31	-	2.31	0.12 (3.05)	
9	2.27	2.28	2.29	2.29	-	2.28	2.30	2.29	2.28	2.27	2.28	2.27	2.29	2.29	2.29	2.28	2.29	2.27	2.29	-	2.30	0.11 (2.79)	
10	2.33	2.33	2.34	2.33	-	2.33	2.35	2.35	2.35	2.35	2.34	2.36	2.35	2.44	2.42	2.43	2.40	2.41	2.45	-	2.45	0.26 (6.60)	
11	2.28	2.28	2.28	2.28	-	2.28	2.30	2.28	2.28	2.29	2.29	2.30	2.30	2.30	2.31	2.32	2.30	2.29	2.32	-	2.32	0.13 (3.30)	
12	2.27	2.27	2.27	2.28	-	2.27	2.29	2.28	2.28	2.27	2.28	2.29	2.29	2.31	2.31	2.33	2.31	2.30	2.34	-	2.34	0.15 (3.81)	
¹ Initial reading. ² Dimension at zero deflection is 55.5 mm (2.19 in.).																							

¹ Initial reading.

² Dimension at zero deflection is 55.5 mm (2.19 in.).

Table B4
Results of SPS Plate Tests Conducted in Arizona

Material Code		Average of Three Deflection Measurements																	Maxi- mum	Deflec- tion ² In. (mm)		
		Time, days																				
		1 ¹	7	14	21	28	35	42	75	105	135	170	200	240	260	320	380	440			500	560
1	2.31	2.31	2.32	2.30	2.30	2.30	2.31	2.31	2.32	2.34	2.37	2.40	2.42	2.36	2.38	2.35	2.42	2.42	2.35	2.45	2.45	0.26 (6.6)
2	2.26	2.24	2.24	2.25	2.27	2.23	2.26	2.28	2.29	2.38	2.38	2.40	2.43	2.45	2.40	2.36	2.41	2.36	2.41	2.45	2.45	0.26 (6.6)
3	2.32	2.31	2.33	2.33	2.32	2.31	2.33	2.37	2.43	2.48	2.53	2.59	2.62	2.54	2.58	2.54	2.61	2.61	2.62	2.59	2.62	0.43 (10.92)
4	2.19	2.19	2.19	2.19	2.19	2.18	2.2	2.2	2.21	2.24	2.25	2.3	2.36	2.37	2.3	2.33	2.28	2.32	2.33	2.4	2.40	0.21 (5.33)
5	2.26	2.27	2.27	2.27	2.27	2.26	2.26	2.27	2.26	2.27	2.26	2.27	2.28	2.27	2.28	2.27	2.28	2.31	2.28	2.31	2.32	0.12 (3.05)
6	2.42	2.46	2.45	2.46	2.45	2.44	2.44	2.51	2.45	2.57	2.54	2.62	2.63	2.65	2.63	2.57	2.58	2.6	2.63	2.64	2.65	0.46 (11.68)
7	2.19	2.25	2.25	2.24	2.23	2.19	2.21	2.21	2.23	2.37	2.47	2.62	2.73	Cracked							2.73	0.54 (13.72)
8	2.25	2.25	2.25	2.25	2.25	2.26	2.25	2.25	2.24	2.25	2.25	2.27	2.29	2.31	2.28	2.31	2.26	2.32	2.39	2.37	2.39	0.20 (5.08)
9	2.33	2.33	2.33	2.33	2.35	2.34	2.33	2.36	2.37	2.42	2.47	2.49	2.52	2.52	2.50	2.46	2.50	2.53	2.50	2.53	2.53	0.34 (8.64)
10	2.16	2.16	2.15	2.15	2.15	2.16	2.15	2.16	2.17	2.20	2.33	2.38	2.45	2.49	2.53	2.50	2.54	2.55	2.54	2.58	2.58	0.39 (9.91)
11	2.24	2.24	2.25	2.25	2.26	2.26	2.26	2.29	2.29	2.33	2.35	2.37	2.38	2.38	2.39	2.39	2.37	2.41	2.40	2.41	2.41	0.22 (5.59)
12	2.24	2.25	2.25	2.24	2.24	2.25	2.24	2.25	2.25	2.26	2.29	2.31	2.34	2.33	2.36	2.34	2.36	2.34	2.35	2.39	2.39	0.20 (5.08)

¹ Initial reading.

² Dimension at zero deflection is 55.5 mm (2.19 in.).

¹ Initial reading.

² Dimension at zero deflection is 55.5 mm (2.19 in.).

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